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Research Document 2002/047 | **Document de recherche 2002/047**

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Physical Environmental Conditions in the Southern Gulf of St. Lawrence during 2001

Conditions du milieu physicque dans le sud du golfe du Saint-Laurent au cours de l'annee 2001

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ISSN 1480-4883
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103-07403/

Abstract

Physical environmental conditions in the southern Gulf of St. Lawrence (Magdalen Shallows) during 2001 were examined from air temperature, sea ice and oceanographic data. Air temperatures over the southern Gulf were above normal through most of 2001, and rose relative to 2000. It was the second warmest year on record in Chatham, N.B. and on the Magdalen Islands and the seventh warmest in Charlottetown, whose records span over 125 years. Warmer air temperatures led to generally less ice than usual over the outer regions of the Shallows towards the Laurentian Channel. However, in the inner reaches, including Northumberland Strait, it was a heavy ice year. Ocean temperatures throughout the Shallows varied spatially, both in the bottom and surface layers. The general trend was towards cooler bottom waters in 2001 as indicated by the large increase in the bottom covered by 0°-1°C water, the generally colder-than-normal temperatures in the 50 to 100 m depth range over the Shallows, the decline in the core temperature of the CIL (cold intermediate layer) throughout the Gulf, and the large portion of the Shallows that recorded below normal temperatures during the fisheries surveys. However, in spite of this general cooler trend, there was a decrease bottom area covered by waters <0°C and significant portions of the Shallows showed above normal temperatures. Also, the surface waters generally showed very high temperatures, reflecting the above normal air temperatures.

Résumé

Les conditions environnementales physiques qui ont prévalu en 2001 dans le sud du golfe du Saint-Laurent (bancs de la Madeleine) ont été examinées en utilisant des données sur la température de l'air, la glace de mer et l'océanographie. Les températures de l'air sur le sud du golfe se sont maintenues au-dessus des normales pendant la grande partie de 2001 et elles ont augmenté par rapport à 2000. On a enregistré la deuxième année la plus chaude à Chatham (N.-B.) et sur les îles de la Madeleine et la septième année la plus chaude à Charlottetown, dont les enregistrements datent de plus de 125 ans. Les températures de l'air les plus chaudes se sont traduites par généralement moins de glace sur les régions externes des bancs vers le chenal Laurentien. Toutefois, dans les zones intérieures, incluant le détroit de Northumberland, la glace a été abondante. Les températures de l'océan dans les bancs ont varié spatialement, dans les couches tant de fond que de surface. La tendance générale a été caractérisée par des eaux de fond plus froides en 2001, tel qu'indiqué par un net accroissement du fond couvert d'eau de 0°-1 °C, des températures généralement plus froides que la normale dans la couche de 50 à 100 m de profondeur sur les bancs, la baisse de la température interne de la CIL (couche intermédiaire froide) dans le golfe au complet et la grande portion des bancs qui ont enregistré des températures sous les normales durant les levés portant sur les pêches. Cependant, malgré cette tendance généralement plus froide, on note une zone de fond moindre recouverte d'eau de <0 °C et des portions importantes des bancs ont affiché des températures plus élevées que les normales. De plus, les eaux superficielles ont eu des températures très élevées, reflétant des températures de l'air plus élevées que la normale.

Introduction

Annual assessments of the stock abundance, fishing effort, and biological characteristics of several groundfish species in the southern Gulf of St. Lawrence (Fig. 1) are undertaken by the Gulf Region of the Department of Fisheries and Oceans (DFO). The purpose of this paper is to provide environmental information as background for these assessments. Air temperatures, sea-ice conditions and ocean temperatures and salinities over the Magdalen Shallows are examined. Conditions during 2001 are described and comparisons are made to conditions in 2000 and the long-term averages. The ocean properties include surface and near-bottom temperatures from the annual groundfish survey plus other fisheries surveys. In addition, vertical profiles and time series of the monthly mean temperatures and salinities within the southern Gulf are provided together with indices of the area of the bottom covered by specified temperatures. We begin with a description of the datasets, then provide details of the methods used to analyze the data and finally present the results.

Data

Air temperature records were available from the Magdalen Islands, Quebec, Charlottetown, Prince Edward Island (PEI) and Chatham, New Brunswick (Fig. 1). Data for 2001 from these sites were obtained from the Environment Canada website and pre-2000 data from the climate indices database at the Bedford Institute of Oceanography (BIO).

Sea-ice data for 2001 covering the entire Gulf of St. Lawrence were obtained from the Canadian Ice Service (CIS). Daily charts were examined to determine the position of the ice edge (10% concentration) at specified dates through the winter. Digital versions of the weekly ice charts from CIS were used to update the gridded sea-ice database at the BIO (Drinkwater et al. 1999). This database contains the concentrations by ice type and the area covered (in tenths) within each 0.5° latitude by 1° longitude for the Gulf of St. Lawrence for the years 1963 to present. From these, we have obtained estimates of the date of first presence of sea ice, last presence and duration of ice during the winter for 2001.

Extensive geographic coverage of surface and near-bottom temperatures during 2001 for the southern Gulf of St. Lawrence was available from three surveys. The mackerel survey was conducted in June (Fig. 2a), the annual snow crab survey during August-October (Fig. 2b) and the annual groundfish survey in September (Fig. 2c). Temperature and salinity data were collected with a conductivity-temperature-depth (CTD) instrument during the mackerel and groundfish surveys. A total of 52 CTD stations were taken on or adjacent to the

Magdalen Shallows during the mackerel survey and 198 stations on the groundfish survey. The snow crab surveys obtained near-bottom temperatures with a thermistor recorder attached to the trawl at 274 stations. Other temperature and salinity data from the southern Gulf in 2001 were obtained from the Marine Environmental Data Service (MEDS) in Ottawa, Canada's national oceanographic data archive, and were derived from research surveys and ships-of-opportunity. Pre-2001 data were taken from the historical hydrographic database maintained at the BIO. This database contains an edited version of the entire MEDS holdings for the region.

Methods

Anomalies, defined as the difference from the long-term averages, were estimated for all of the environmental data. Where possible, the long-term averages were calculated over a 30-year period (1971-2000) in accordance with the convention used by the meteorologists and adopted for use with oceanographic data by the DFO's Fisheries Oceanography Committee and the Scientific Council of the North Atlantic Fisheries Organization (NAFO). Note that last year (Drinkwater et al., 2001) we used the long-term averaging period 1961-1990, but again in keeping with the Canadian meteorological convention, the 30-year period has been updated to the period including the three most recent decades, i.e. 1971-2000.

The surface and near-bottom temperatures from data collected during all of the surveys were interpolated onto a specified grid using an objective analysis procedure known as optimal estimation. This method is similar to other objective techniques such as kriging but offers the advantage that the interpolation is 4-dimensional; i.e. three space dimensions, two horizontal and one vertical, and the time dimension, rather than 2-dimensional (the two horizontal dimensions). In this study the surveys were treated as synoptic and no interpolation in time was carried out. The details of the procedure are found in Drinkwater and Pettipas (1996). For the surveys using CTDs, the maximum profile depth from the CTD trace for each station was assumed to be at the bottom. Checks against bathymetric charts were carried out to ensure no large errors occurred as a result of this assumption. The maximum depth in the grid for the slope water area off the Scotian Shelf was taken as 1000 m. The temperature grid for the Gulf of St. Lawrence was 0.1° x 0.1° latitude-longitude. The bottom temperature data were then smoothed for the purpose of contouring. Note that the smoothing routine tends to spread out sharp near-bottom temperature gradients (e.g. those near the coast), thus the gradients depicted in the plots are not as sharp as in reality.

Long-term monthly climatological means of the surface and near-bottom temperatures were estimated at each grid point based upon optimal estimations using all available data for the years 1971-2000 in the historical temperature,

salinity database at the BIO. Temperature anomalies were derived by subtracting these climatological means from the 2001 values. A negative anomaly indicates that the 2001 temperature was colder than the long-term mean and a positive anomaly indicates that it was warmer than the long-term mean. We also examined the change in temperature since the previous year by subtracting the 2000 optimally-estimated temperatures from the 2001 estimates. A negative value indicates that 2001 was cooler than 2000, a positive value that it was warmer.

From the optimally-estimated bottom temperatures obtained during the groundfish survey, the area of bottom covered by each 1C° temperature bin was estimated for the entire series (1971-2001). For this, the temperature at each grid point was assigned the area of bottom associated with that particular grid point. These have been used to estimate the amount of bottom covered by water of <0°C and <1°C.

In addition, monthly mean temperature profiles for 2001 were determined within the eastern and western regions of the Magdalen Shallows from the BIO database. All available data within each of these areas were averaged by month at standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 175, 200, 250, and 300 m where possible). An "annual" anomaly profile was determined by averaging the available monthly anomalies, regardless of whether there were 1 or 12 months. Time series of monthly mean temperatures and salinities at representative depths for each area are also provided. Long-period trends are shown in the plots of these monthly means. They are the 5-year running averages of the "annual" anomalies.

Results

Air Temperatures

The mean air temperatures on the Magdalen Islands were warmer than their long-term average in 11 of the 12 months of 2001 (Fig. 3). Warmer-than-normal air temperatures also were observed at Charlottetown and Chatham, although they had more months with below average values (4 and 2 months, respectively). The annual means were above normal at all three sites (Magdalen Islands, anomaly of 1.6°C; Chatham, 1.6°C; Charlottetown, 0.9°C). The time series at each of the sites show similar trends (Fig. 4, 5). The longest record is from Charlottetown, which began in 1873. It shows that in most years prior to 1930 the annual mean temperatures were below the 1971-2000 average. Since the 1950s, there has been a tendency to exhibit oscillations with an approximate 15-year period. Recent temperatures have been well above normal with 1999 having the highest temperature on record at all three sites and 2001 being the second highest on the Magdalen Islands (in 68 years) and at Chatham (in 59 years) and the 9th warmest at Charlottetown (in 128 years).

Sea-ice

The location of the ice edge within the Gulf of St. Lawrence at various times during the winter season is shown in Fig. 6. These represent snap shots and it must be remembered that the ice edge can vary rapidly over short periods of time. In the latter half of December, strong winds and warm air temperatures caused destruction of the ice that had formed earlier in the month and also slowed ice formation. There was about the usual amount of ice on the Shallows, which was restricted to the coastal regions including Northumberland Strait. By mid-January the ice coverage was generally less than normal due to mild air temperatures and the passage of a series of storms during the month. The northern region of the Shallows and off northern Prince Edward Island became ice-covered by the end of January but the southern region remained open. Usually at this time of the year, the entire Magdalen Shallows are covered with ice. Due to persistent north to northwesterly winds and below normal temperatures during the second half of February, ice drifted rapidly southeastward such by 1 March the Shallows were essentially ice covered. With frequent storms during March, the ice began to break-up and by 1 April ice had disappeared from most of the region. The ice that did remain was primarily located in the southern sections. This ice continued to break up and melt and by late April there was no ice left over the Shallows.

The times of first presence of ice show ice forming initially along the coastal regions of the Magdalen Shallows and spreading eastward (Fig. 7). By the end of January, ice had covered all of the Shallows for at least some period of time. Subtracting the long-term (1971-2000) mean, indicates that the time of first ice was early over most of the Shallows with it appearing >10 days early along the coastal regions and >20 days in St. Georges Bay, off northeastern Prince Edward Island and around the Magdalen Islands (Fig. 7). Exceptions were the northern outer regions and between the Magdalen Islands and eastern PEI where the ice was later than normal. The last presence of ice varied from near the end of March (day 90) to the end of April (day 120), resulting in it disappearing up to 10 days earlier than normal in the region between the Magdalen Islands and the Gaspé but over 10 days later than normal in many of the coastal regions from Cape Breton to the Bay of Chaleur (Fig. 8). The duration of sea ice is the number of days ice was present. It is not the simple difference between the dates of first presence and last presence since the ice may appear and disappear during the ice season. On the Shallows the duration varied from a high of over 140 days around Miramichi Bay and in Northumberland Strait to 60 days along its outer edge adjacent to the Laurentian Channel (Fig. 9). This resulted in durations that were up to 20 days less than normal at this offshore edge to 20 days longer than normal in the inner coastal regions (Fig. 9).

Hydrographic Conditions

Bottom Temperatures

The mackerel survey in June 2001 shows a large area of the central Shallows covered by temperatures <0°C (Fig. 10). From there, bottom temperatures tended to increase towards the shallower, nearshore regions and towards the deeper Laurentian Channel. This is because in the Gulf of St. Lawrence throughout the summer, cold temperatures are found at intermediate depths (50-150 m), sandwiched between warm solar-heated upper layer waters and the relatively warm, salty deep waters in the Laurentian Channel. The cold waters are known as the cold intermediate layer (CIL). In winter, the CIL merges with the upper layer as the latter cools. The primary origin of the waters in the CIL is from atmospheric cooling of the water within the Gulf of St. Lawrence in winter with an additional 35% from advection of cold Labrador Shelf water through the Strait of Belle Isle (Petrie et al., 1988). The warmer waters in the deeper layers originate from the Atlantic Ocean in the region between the continental shelves and the Gulf Stream known as the Slope Water region. Although these waters are warmer than the CIL, their density is greater because of higher salinities.

Relative to the long-term (1971-2000) mean, the bottom temperatures in June 2001 tended to be colder than average over most of the Shallows (Fig. 10). The largest negative anomalies (below -2°C) were located between PEI and the Bay de Chaleur and south of the Magdalen Islands. The notable exceptions to the cold conditions were areas over the central Shallows and in the Bay de Chaleur where temperatures were slightly above there long-term average. Relative to the mackerel survey in 2000, temperatures had cooled over most of the bottom with differences of upwards of 4°-5°C off eastern PEI. Again, the major exception to this trend was in the central area of the Shallows (Fig. 11).

The longest running survey on the Magdalen Shallows is the September groundfish survey (1971-present). During 2001, data collected during this survey showed bottom temperatures ranging from <1°C to over 17°C (Fig. 12). The majority of the bottom was covered by temperatures of <3°C, with the largest portion of the Shallows <1°C. The warmest near-bottom temperatures in the southern Gulf were in its shallowest regions, in particular, in Northumberland Strait and in St. Georges Bay (Fig. 12).

Temperature anomalies during September over most of the Shallows were near to or just above normal (Fig. 12). The exception was a band of below average temperatures stretching offshore of Cape Breton Island, north of Prince Edward Island and northward towards the Gaspé. The highest negative anomalies appeared off eastern Prince Edward Island. The warmest anomalies (above 2°C) were located in Miramichi Bay. However, high anomalies in nearshore regions must be viewed with caution since these regions contain the largest uncertainties in

the optimally-estimated temperature fields. There are two main reasons for this. First, there tends to be greater temporal variability at shallower depths because they lay close to the strong vertical gradient in temperature, called the thermocline by oceanographers. Indeed, in these regions the mixed layer may at times extend to the bottom in response to wind storms producing large variability in the near-bottom temperatures. Second, the optimal estimation routine extrapolates horizontal temperature gradients to the coast if there are no data inshore. This can lead to fictitious data, especially in regions of strong gradients.

Relative to 2000, bottom temperatures during the 2001 groundfish survey tended to be near to or slightly warmer over the central Magdalen Shallows north of Prince Edward Island (Fig. 13). In contrast, temperatures cooled between the Magdalen Islands and Cape Breton island, immediately to the north of Prince Edward Island, along the southern edge of the Laurentian Channel and off much of the Gaspé Peninsula. Cooling was greatest (upwards of 4°C) off eastern Prince Edward Island. This pattern is similar to that from the mackerel survey (Fig. 11).

Using the gridded temperatures from the groundfish survey, time series of the area of bottom covered by each 1C° bin were estimated. We have plotted the time series of the area of the bottom covered by <0°C and <1C° waters following Swain (1993) who first used this index. In 2001, there was an increase in area covered by <1°C but a decline in the area covered by temperatures <0°C relative to 2000 (Fig. 14).

The spatial pattern of the bottom temperatures from the snow crab survey in August-October 2001 (Fig. 15) is similar to that from the 2001 groundfish survey (Fig. 12). The major difference is the warmer values in the Bay of Chaleur and other nearshore regions during the groundfish survey. In the deeper regions (>~50 m), the temperature and temperature patterns are similar, although not identical. For example, there is slightly more <1°C water recorded in the snow crab survey. However, over 84% of the gridded temperatures from the two surveys differ by <0.5°C for the same grid point and 94% were within 1°C. Possible causes of the differences besides seasonal warming in the shallow regions may be differences in instrument accuracy (the CTD being more accurate than the thermistor recorder), a relative rapid point measurement (CTD) versus an average over a trawl distance (snow crab survey), and the difference in depth of the measurement (the thermistor is on bottom while the CTD will be a few to several m above the bottom.

Surface Temperatures

In addition to the near bottom temperatures, we have investigated the surface (0-5 m) temperatures from the surveys. In the June mackerel survey, surface temperatures over the Shallows ranged from 8°C in the Laurentian Channel region to over 15°C off PEI and New Brunswick (Fig. 16). Temperatures generally

increased towards the northwest. The 2001 surface values tended to be above their long-term means in the area between eastern PEI, the Magdalen Islands and the Gaspé. Warm conditions also were observed off western Cape Breton. Adjacent to the Laurentian Channel, south of the Magdalen Islands and off eastern PEI temperature anomalies were negative. The highest anomalies appeared off Chaleur Bay. The change in surface temperatures between 2000 and 2001 varied spatially (Fig. 17). Temperatures cooled in the areas off the Gaspe, along the Laurentian Channel, off eastern and northern PEI, and along southwestern Cape Breton and warmed elsewhere.

The surface temperatures from the groundfish survey in September ranged from 10°C off Gaspe to over 19°C in Northumberland Strait and St. Georges Bay (Fig. 18). The surface waters over the southern half of the Shallows were warmer their long-term means by upwards of over 2°C. In the outer Shallows area, closer to the Laurentian Channel, the surface temperatures were below average, however. This general pattern bares a resemblance to that from the mackerel survey (Fig. 16). The change in the surface temperatures between the groundfish surveys from 2000 to 2001 are similar to the anomaly pattern with warmer temperatures in 2001 in the inner portions of the Shallows and colder further offshore (Fig. 19).

Monthly Mean Temperatures and Salinities

Vertical profiles of the monthly mean temperature and salinity anomalies for the southern Gulf were calculated from all available data. As in last year's report (Drinkwater et al., 2001), we examined possible spatial differences in temperature trends across the Magdalen Shallows by dividing it into eastern and western regions for the purposes of our analysis (see Fig. 20 for the area boundaries used in the temperature analysis). The monthly mean temperatures and salinities at standard depths were estimated by averaging all of the available data within each region regardless of when in the month it was collected. Similarly, no adjustments were made for the spatial distribution of data or the amount of data that contributed to the average. In some cases the "average" was based upon only one measurement while in other months it was over 100 stations. The long-term (1971-2000) means for each area were calculated and then subtracted to obtain an anomaly. The monthly anomalies within the calendar year were then averaged to obtain an "annual" anomaly. In addition to the vertical profiles, time series of temperature and salinity anomalies at 0 m and 75 m are presented. The latter depth is considered representative of the near-bottom within both regions. Because of the possible limited amount of data from which the averages were made or the spatial variability in temperature within the regions, any one point or profile may not be truly representative of "average" conditions for the month. Interpretation of the anomalies therefore must be viewed with caution. While no significance should be placed on any individual monthly anomaly, persistent features are considered to be real.

Data for 2001 over the western Magdalen Shallows were available for 9 months (April to December inclusive). The monthly anomaly profiles tend to show variable temperatures between 50 and 100 m but a tendency towards slightly colder than average (Fig. 21). This is reflected in the "annual" mean profile where at 75 m the annual mean temperature anomaly was approximately –0.25°C and is statistically different from zero (Fig. 21). In contrast, the upper 30 m show warm conditions with monthly anomalies of 3°-4°C and an average through the year of 1°-2°C. The only major exceptions to the warm upper layer temperatures was in May and June. Salinities were generally fresher-than-normal over most of the deeper waters of the Shallows (below 50 m) whereas in the surface layers (0-10 m) they were saltier-than-normal (Fig. 22). At 20 and 30 m depths, they varied with an annual mean not statistically different from zero. These salinity conditions are opposite to what was observed in 2000.

On the eastern side of the Shallows, data were available in 6 of the 12 months in 2001. Absolute temperatures were marginally warmer than in the west but the anomalies showed similar trends in both regions. Thus, in the eastern region waters in the deep layers (75 m to 100 m, which corresponds to the bottom depth over most of the Shallows) were typically colder (Fig. 23) and fresher (Fig. 24) than the long-term average. The upper layer (0 m to 30 m) was warmer and saltier-than-normal. The warm conditions appeared to penetrate to deeper depths in the east than in the west and the maximum depth to which the colder-than-normal temperatures were observed was also deeper.

In addition to the anomaly profiles, time series of the monthly mean temperature and salinity anomalies at 75 m and the surface were generated. Note that data are not available in every month. There are less salinity data and hence the long-term trends for salinity are not as reliable as for temperature. Although there are some differences in the temperatures in the two sides of the Shallows at 75 m, the long-term trends in both regions are similar (Fig. 25). Relatively warm conditions persisted around the mid-1950s, near 1970, and in the early 1980s separated by colder-than-normal periods. The late 1980s and 1990s exhibit the longest period of below average temperatures in the entire record. While the last couple of years have seen warming from these low temperatures, the eastern side of the Shallows experienced above normal temperatures in 2000 while the western side showed colder-than-normal conditions. In 2001, both regions showed a tendency towards below normal values. The monthly time series at the surface show much higher variability than at 75 m (Fig. 26). This is because the atmospheric heat fluxes that warm and cool the surface waters undergo large changes from month to month. The surface temperature trends showed much less similarity between the two sides of the Shallows than at 75 m. Surface layer waters were warm in the late 1940s and 1950s, near normal through most of the 1960s, warm around 1980 and slightly above normal through the 1980s and into the 1990s. The late 1990s showed higher positive temperature anomalies than the previous decade. These

warm surface conditions have continued into 2000 and 2001. The salinities at 75 m show several differences between the two regions but this may be due in part to the small number of samples. In recent years, including in 2001 there appears to be fresher-than-normal salinities near bottom on both sides of the Shallows (Fig. 27). Surface salinities through the late 1990s to 2001 have been generally saltier-than-normal on the eastern side of the Shallows (Fig. 28). In the west, the anomalies have been smaller and there has been greater variability with many more negative anomalies indicating fresher-than-normal conditions. In 2001, however, surface conditions in the west were generally saltier-than-normal.

CIL Core Temperature

Gilbert and Pettigrew (1997), in a study of the cold intermediate layer (CIL), produced a Gulf-wide index of the core temperature for mid-July based upon available observed data and the mean measured warming rate. This index has continued to be updated by Dr. D. Gilbert who kindly provided us with the data. During 2001, the CIL mid-summer core temperature was -0.42°C (representing an anomaly of -0.17°C), and was colder than 2000 by over 0.5°C (Fig. 29). This was the largest single year decline in the core temperature in the past 30 years and returns it to values of the cold period from the mid-1980s through the 1990s. Gilbert and Pettigrew (1997) found high correlations between the variability in the CIL core temperatures and air temperatures along the coast of western Newfoundland, suggesting the possible importance of atmospheric forcing in determining the temperature and extent of the CIL waters in the Gulf. However, these air temperatures were above normal during 2001, which cannot explain the large decline in core temperature of the CIL. Recent reports suggest that the cold temperatures may be related to an intrusion of water from off the Labrador Shelf through the Strait of Belle Isle (D. Gilbert, Maurice Lamontagne Institute, personal communication).

Summary

Physical environmental conditions in the southern Gulf of St. Lawrence (Magdalen Shallows) during 2001 were examined from air temperature, sea ice and oceanographic data. Air temperatures over the southern Gulf were above normal through most of 2001, and increased relative to 2000. At Chatham and on the Magdalen Islands, air temperatures were the 2nd warmest on record with only 1999 being warmer. Less sea-ice of shorter duration was observed in the outer regions of the Magdalen Shallows but more ice of longer duration than normal was found in the Northumberland Strait and in the inner portion of the Shallows. Surface temperatures over the Shallows tended to be warmer-than-normal throughout most of the year. This parallels the warm air temperatures. Subsurface temperatures were generally colder than the long-term average. This was evident by the increase of bottom temperatures <1°C, the extensive regions of the Shallow covered by colder-than-average temperatures, the decline in the core temperature of the CIL and the below normal temperatures in both the eastern and western

sides of the Shallows in the depth range of 75 m. In spite of the cooling trend, the amount of <0°C waters on the bottom during the groundfish survey declined and significant areas of the Shallows had above normal bottom temperatures. The western and eastern regions of the Shallows showed less differences in temperature and salinity in 2001 than they did in 2000.

Acknowledgements

We gratefully acknowledge J. McRuer at BIO for providing the CTD data from the groundfish surveys and M. Moriyasu, M. Biron and R. Gautreau at GFC in Moncton for temperature data from the snow crab surveys. The mackerel survey data were collected by scientists at IML in Mont Joli, Quebec, headed by F. Gregoire. D. Gilbert at IML supplied the CIL core-temperatures. We extend a special thanks to the scientists, technicians and crew who collected the data used in this report.

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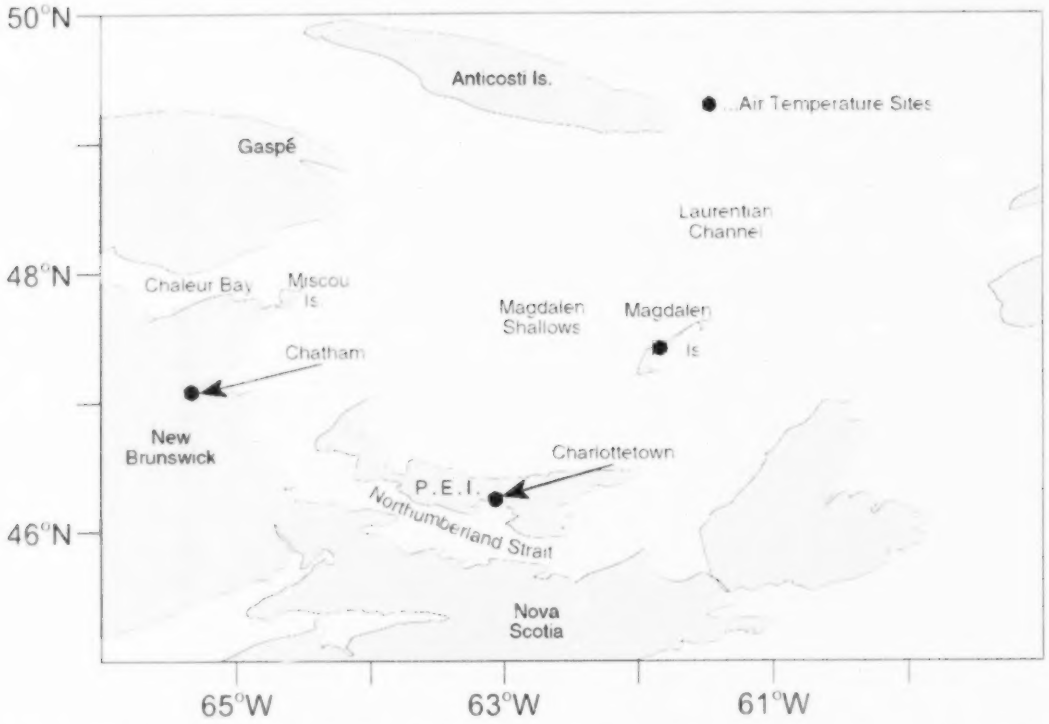

Fig. 1. Chart of the southern Gulf of St. Lawrence showing geographic and topographic features referred to in the text. Air temperature sites are also shown.

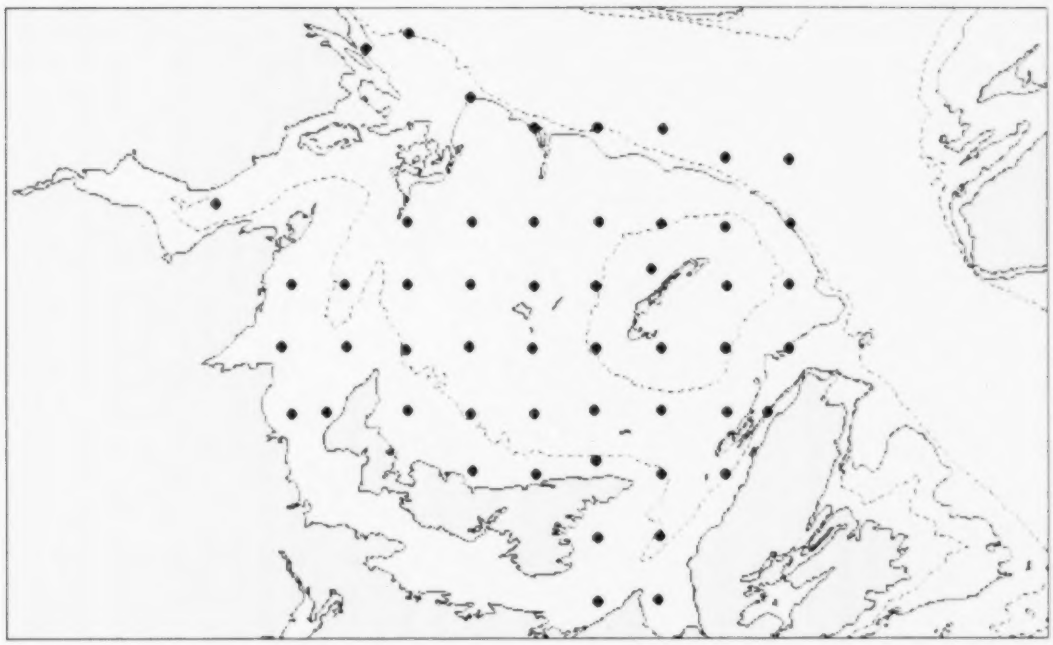

Fig. 2a. The location of the CTD temperature stations during the June 2001 mackerel survey.

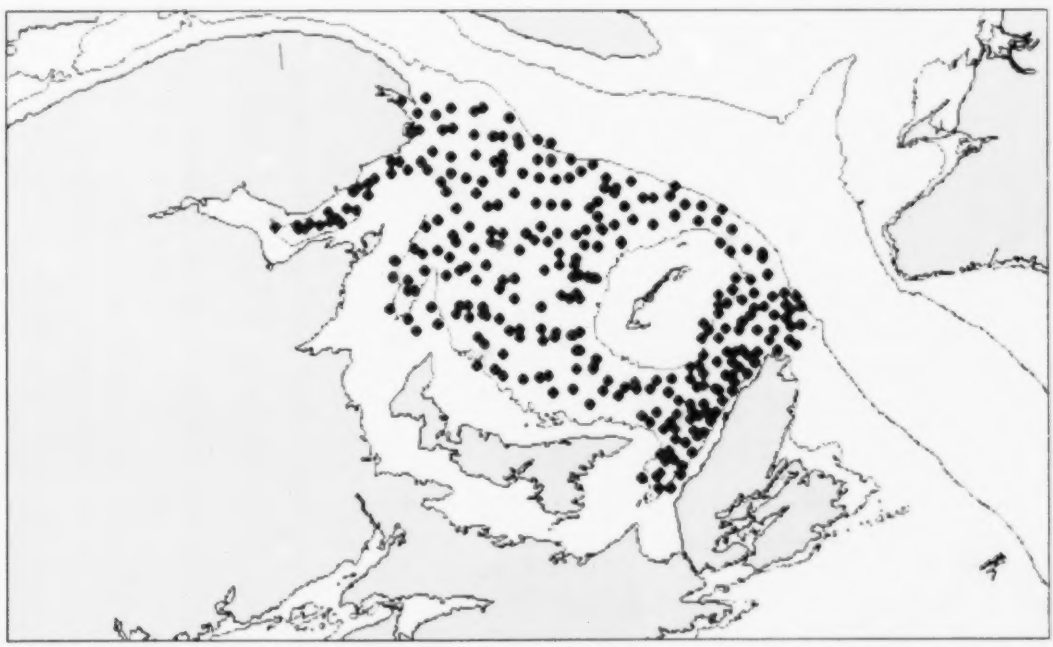

Fig. 2b. The location of the bottom temperature stations during the August-October 2001 snow crab survey.

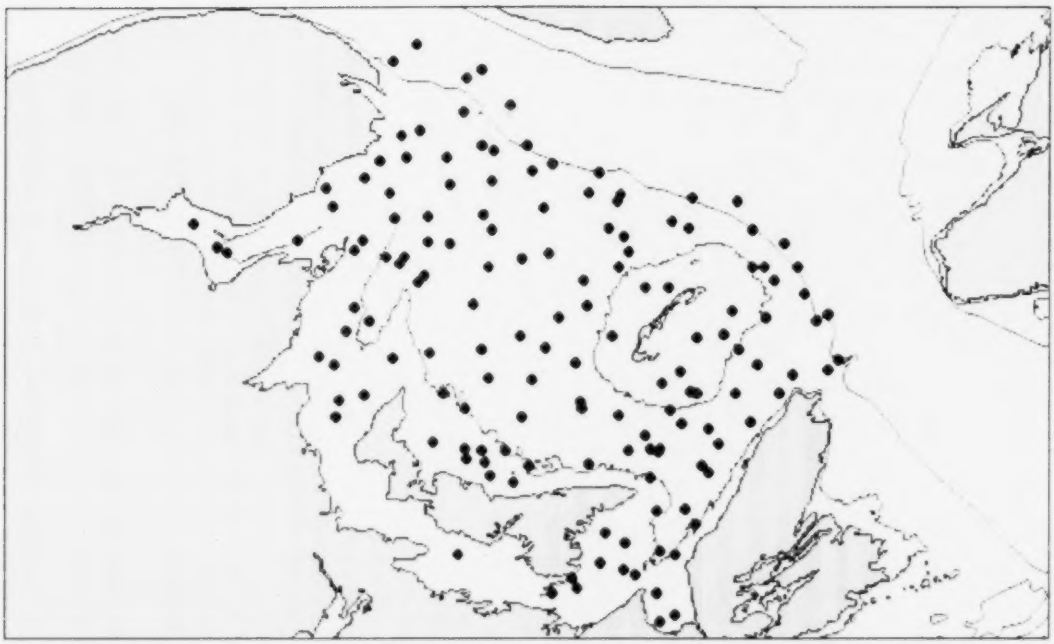

Fig. 2c. The location of the CTD stations during the September 2001 survey.

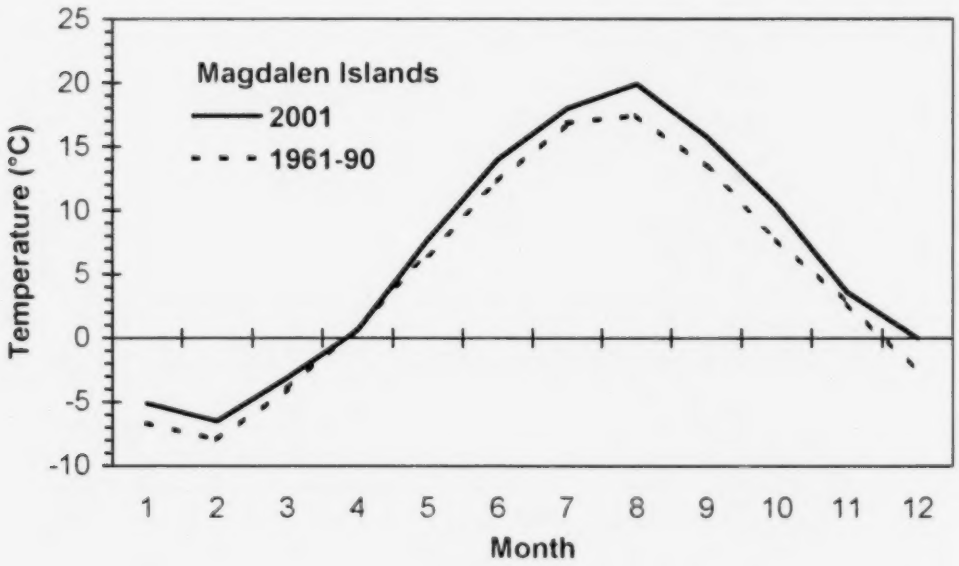

Fig. 3. The monthly mean air temperatures for the Magdalen Islands in 2001 and their long-term averages (1971-2000).

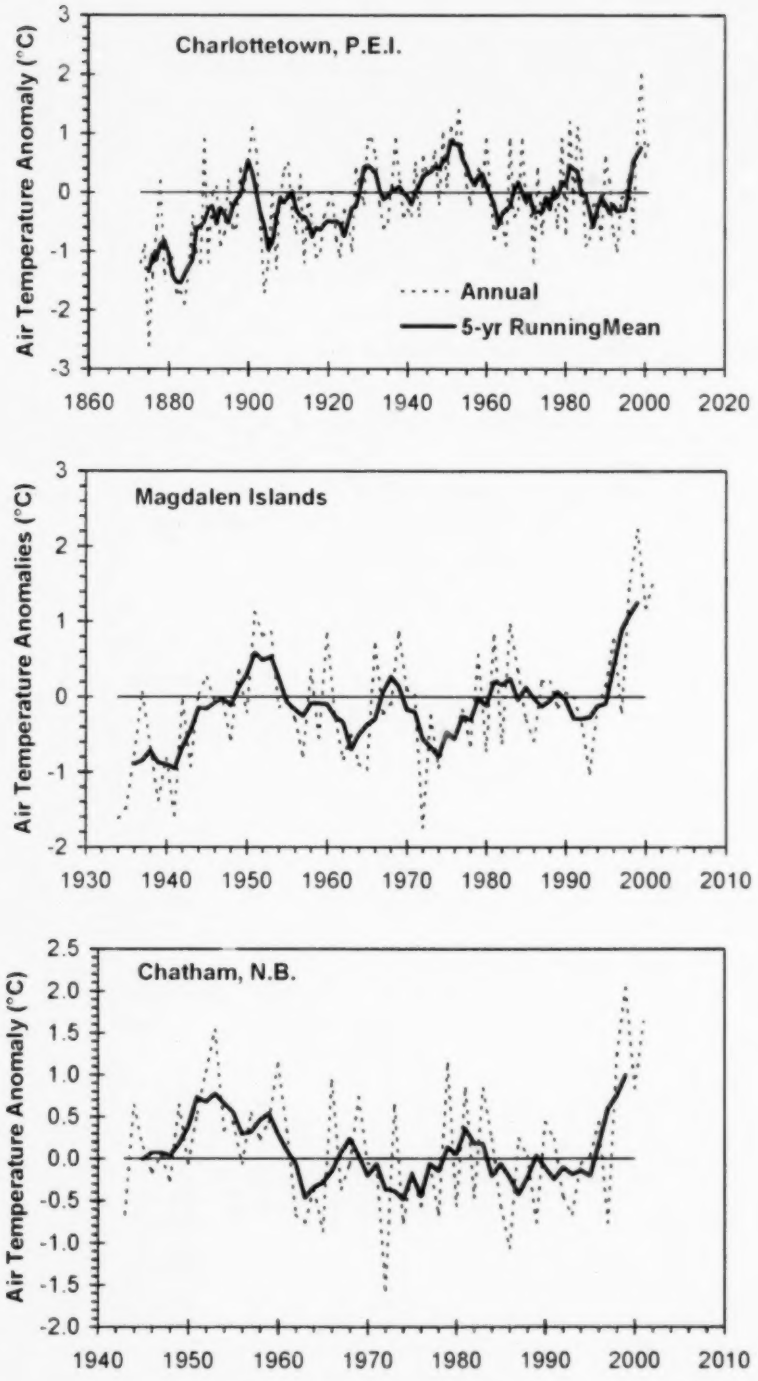

Fig. 4. Time series of the annual air temperature anomalies relative to 1971-2000 (dashed lines) and their 5-year running means (solid lines) for Charlottetown, the Madgalen Islands and Chatham. Note the axis scales on all three diagrams are different.

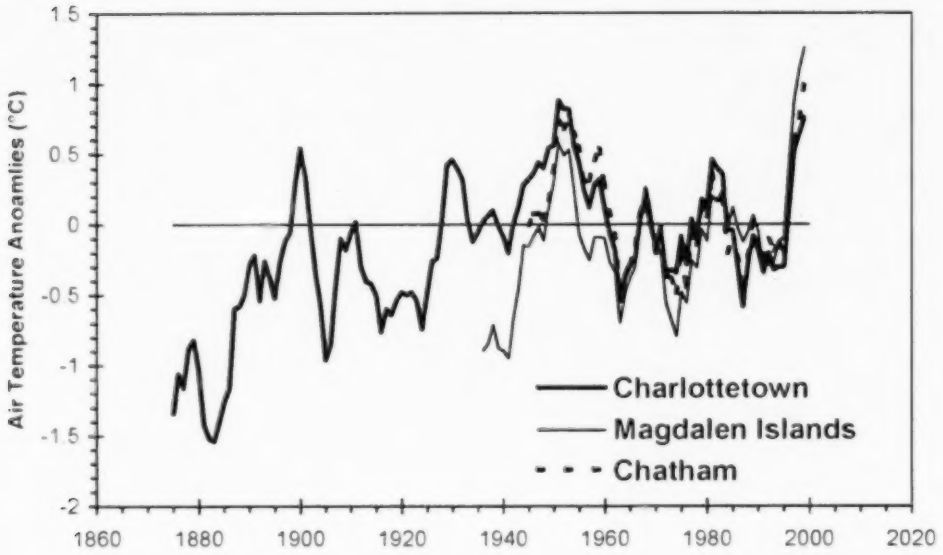

Fig. 5. The time series of the 5-year running means of air temperature anomalies relative to 1971-2000 at three sites in the southern Gulf of St. Lawrence.

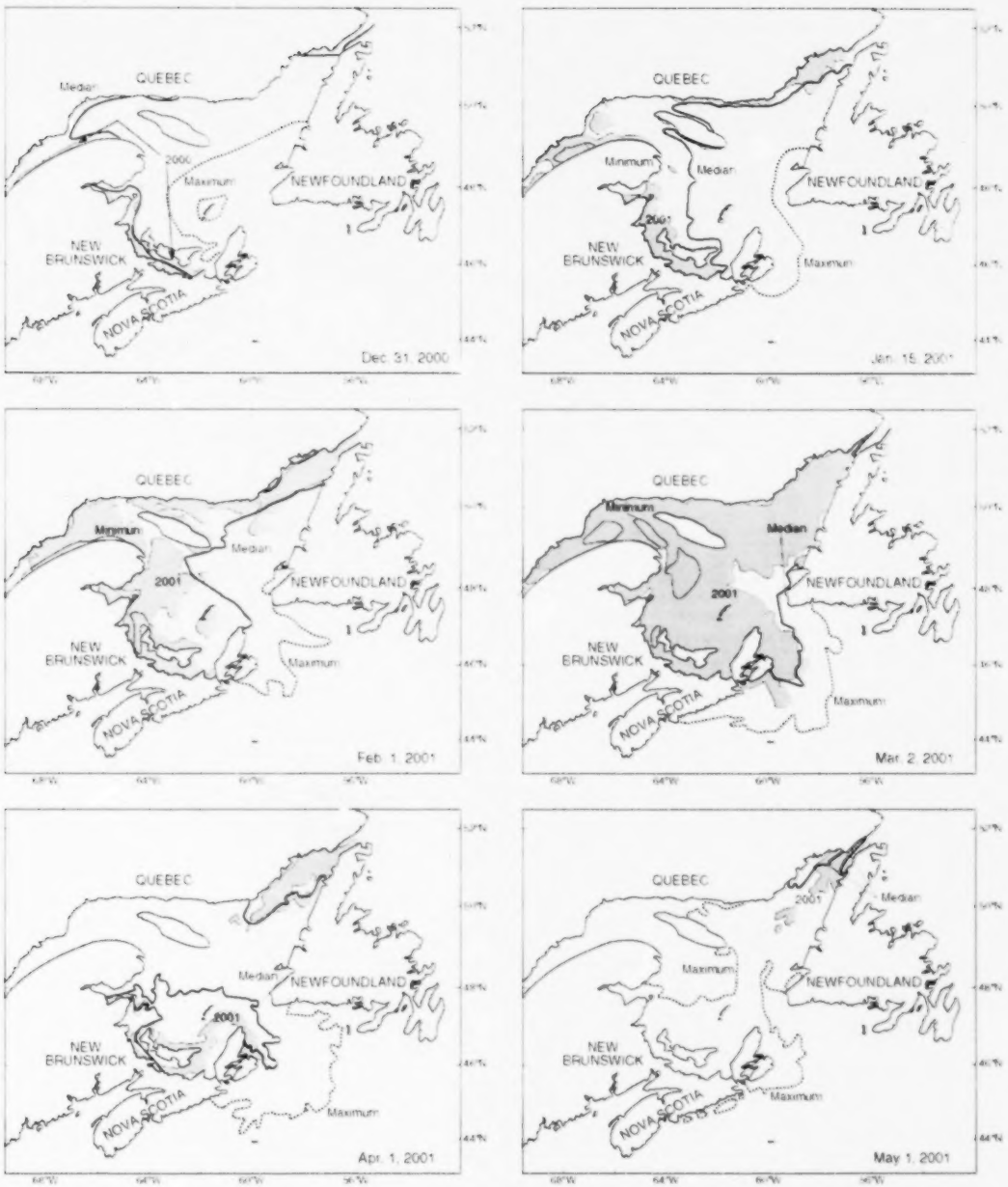

Fig. 6. The location of the ice (shaded area) between 31 December 2000 to 1 May 2001 together with the historical (1962-1987) minimum, median and maximum positions of the ice edge in the Gulf of St. Lawrence.

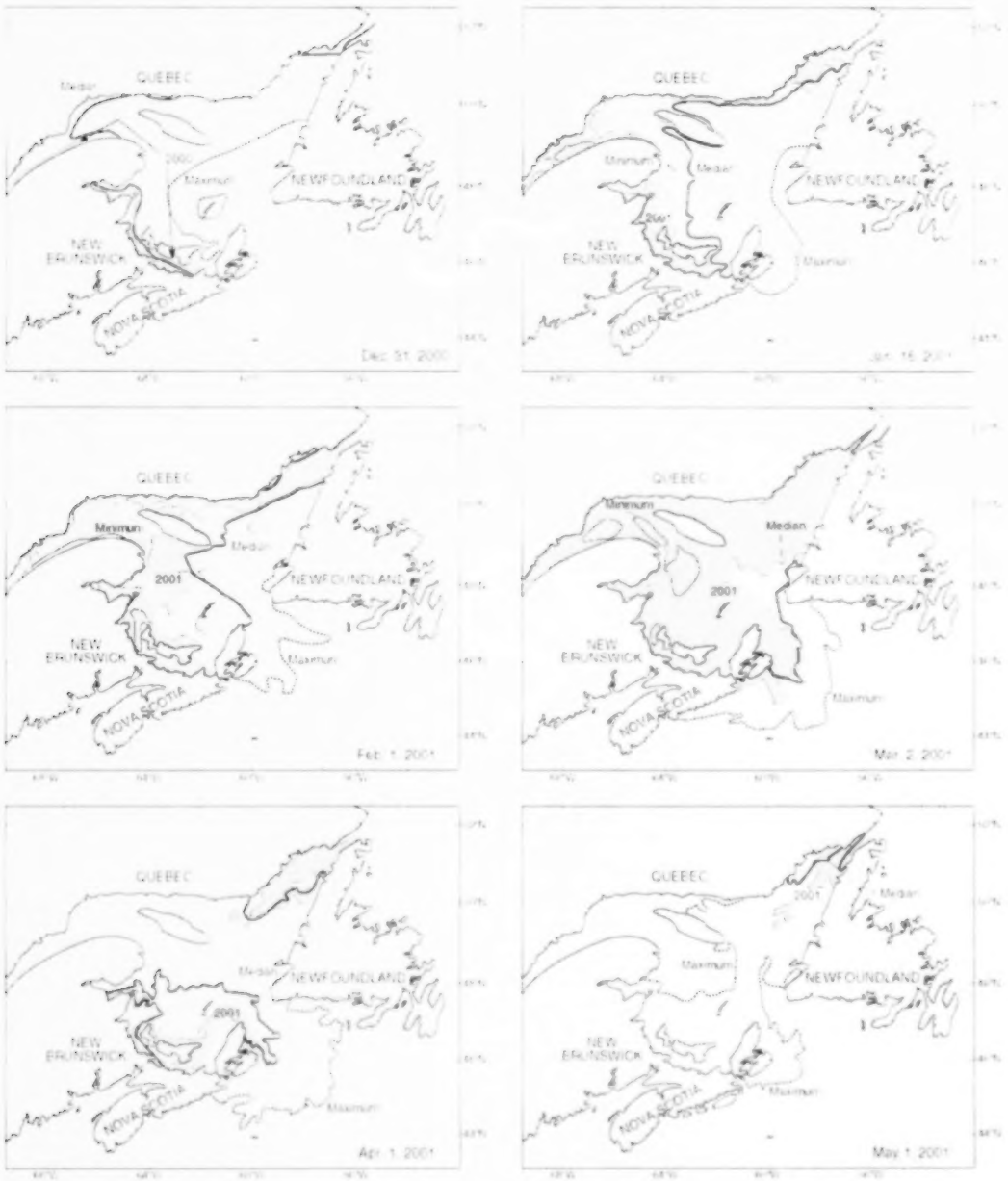

Fig. 6. The location of the ice (shaded area) between 31 December 2000 to 1 May 2001 together with the historical (1962-1987) minimum, median and maximum positions of the ice edge in the Gulf of St. Lawrence.

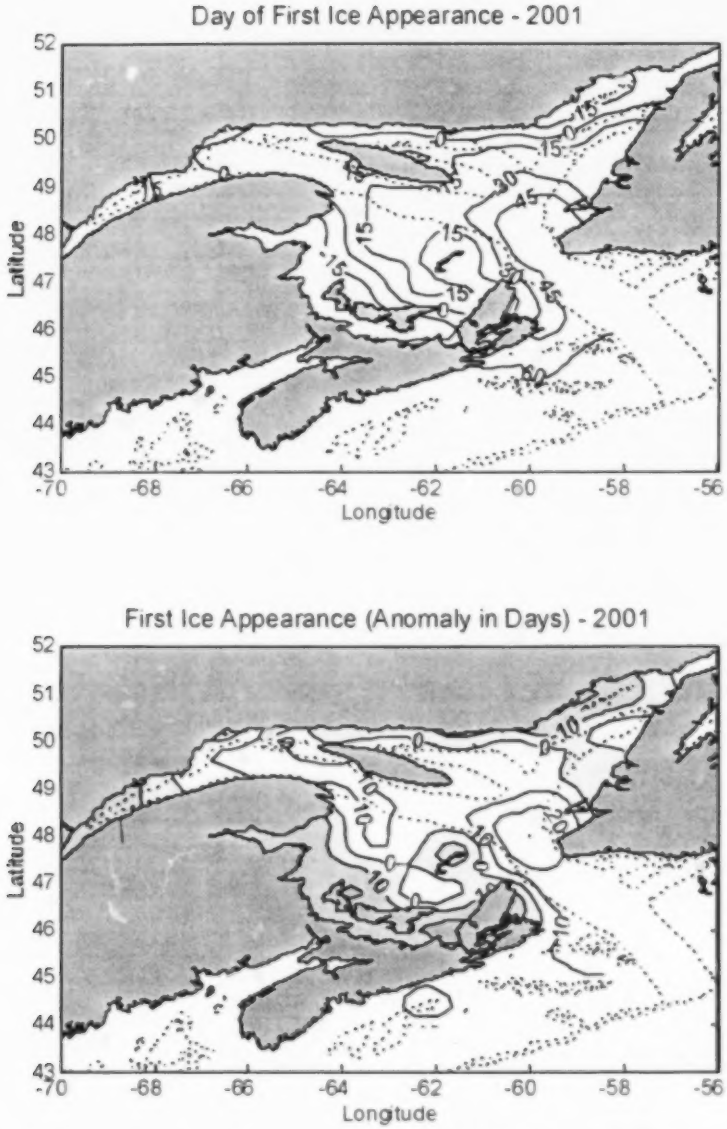

Fig. 7. The time when ice first appeared during 2001 in days from the beginning of the year (top panel) and its anomaly in days from the 1971-2000 mean in days (bottom panel). The shaded regions in the bottom panel indicate negative anomalies, i.e. where ice appeared early.

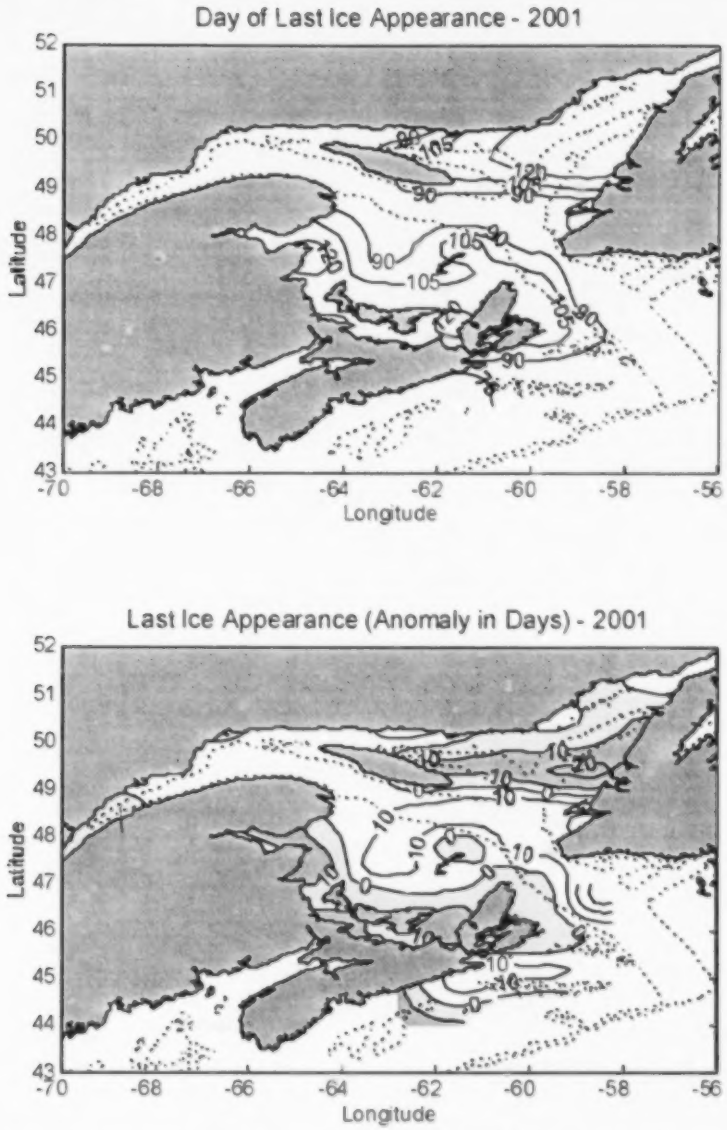

Fig. 8. The time when ice last appeared during 2001 in days from the beginning of the year (top panel) and its anomaly from the 1971-2000 mean in days (bottom panel). The shaded regions in the bottom panel indicate negative anomalies, i.e. where ice left late.

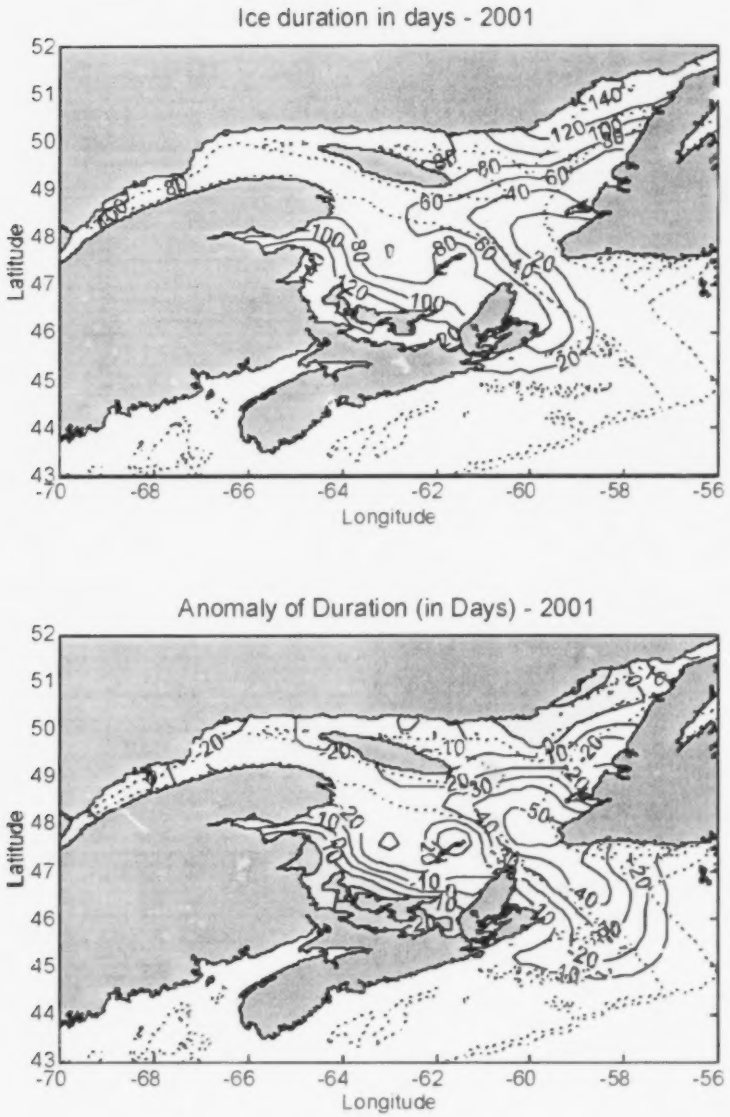

Fig. 9. The duration of sea-ice in days (top panel) during 2001 and their anomaly from the 1971-2000 mean in days (bottom panel). Note that the shading denotes regions where the duration was greater than average (positive anomalies).

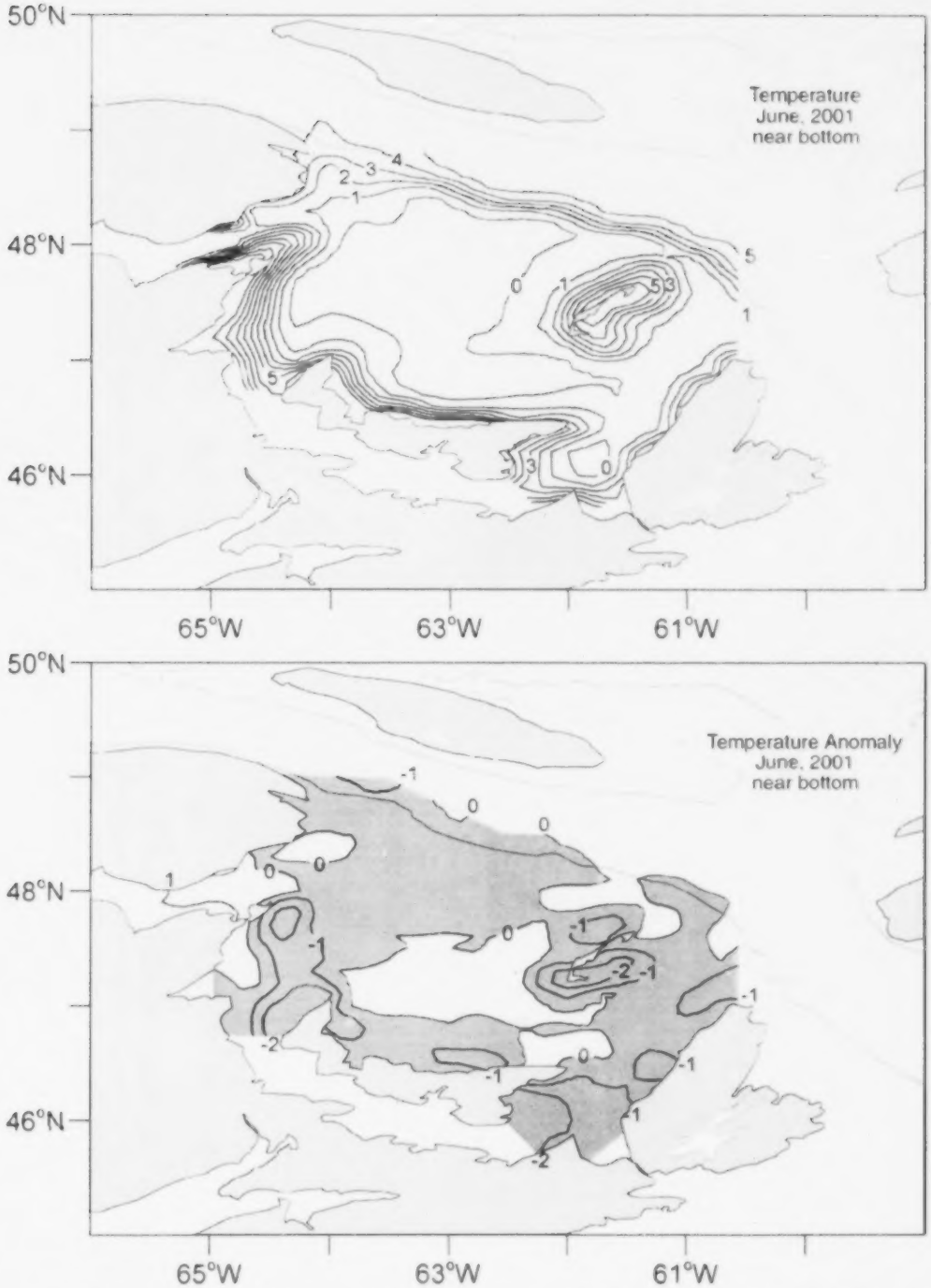

Fig. 10. Near-bottom temperatures (top panel) and their departure from the long-term (1971-2000) means (bottom panel) in the southern Gulf of St. Lawrence during the 2001 June mackerel survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

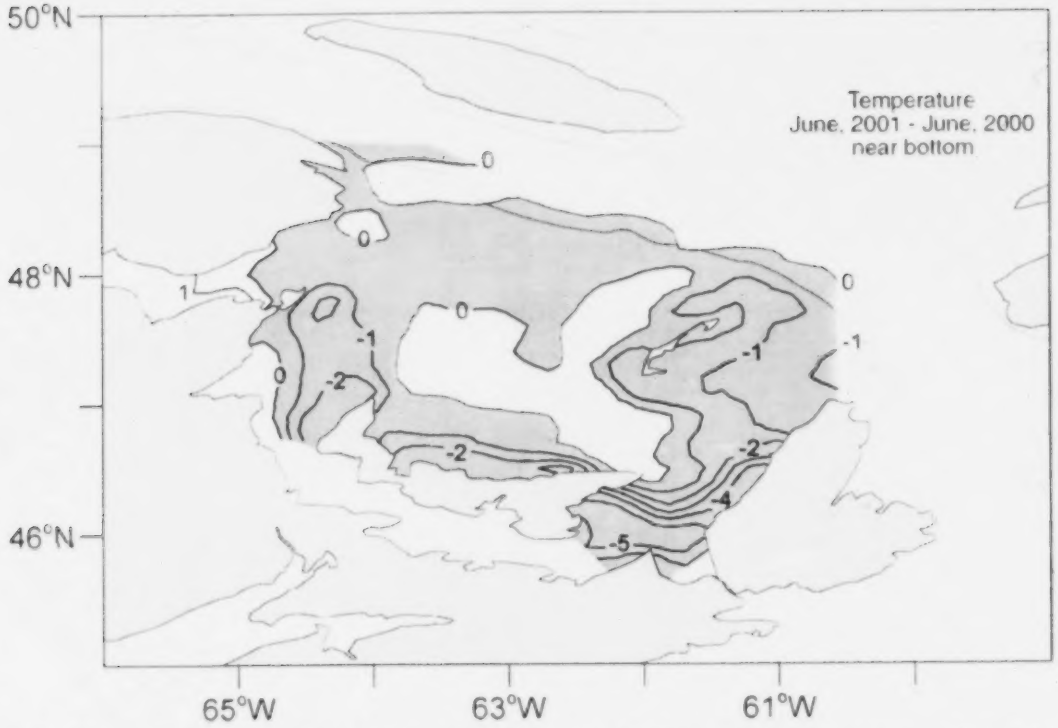

Fig. 11. The difference between the 2001 and 2000 near-bottom temperatures in the southern Gulf of St. Lawrence for the June mackerel survey. Positive values indicate temperatures in 2001 had warmed and negative values (shaded) where they had cooled.

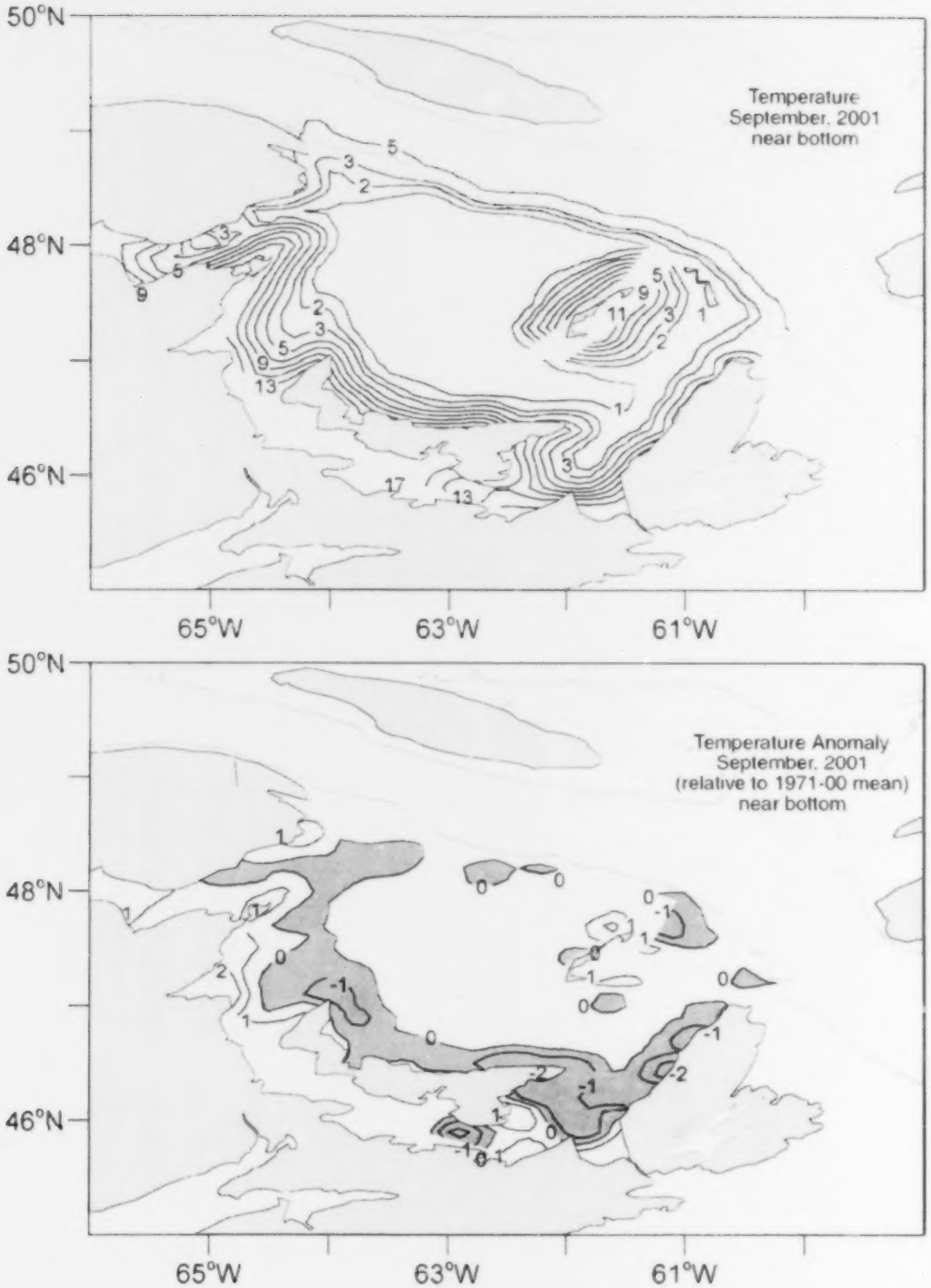

Fig. 12. Near-bottom temperatures (top panel) and their departure from the long-term (1971-2000) means (bottom panel) in the southern Gulf of St. Lawrence during the 2001 September groundfish survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

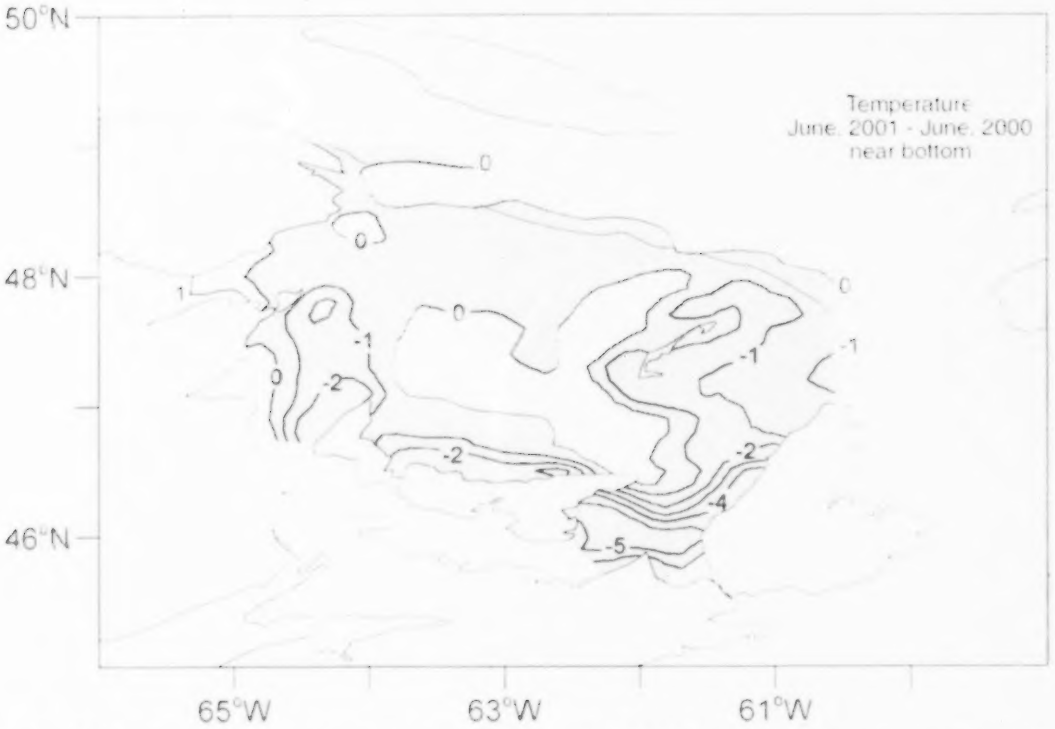

Fig. 11. The difference between the 2001 and 2000 near-bottom temperatures in the southern Gulf of St. Lawrence for the June mackerel survey. Positive values indicate temperatures in 2001 had warmed and negative values (shaded) where they had cooled.

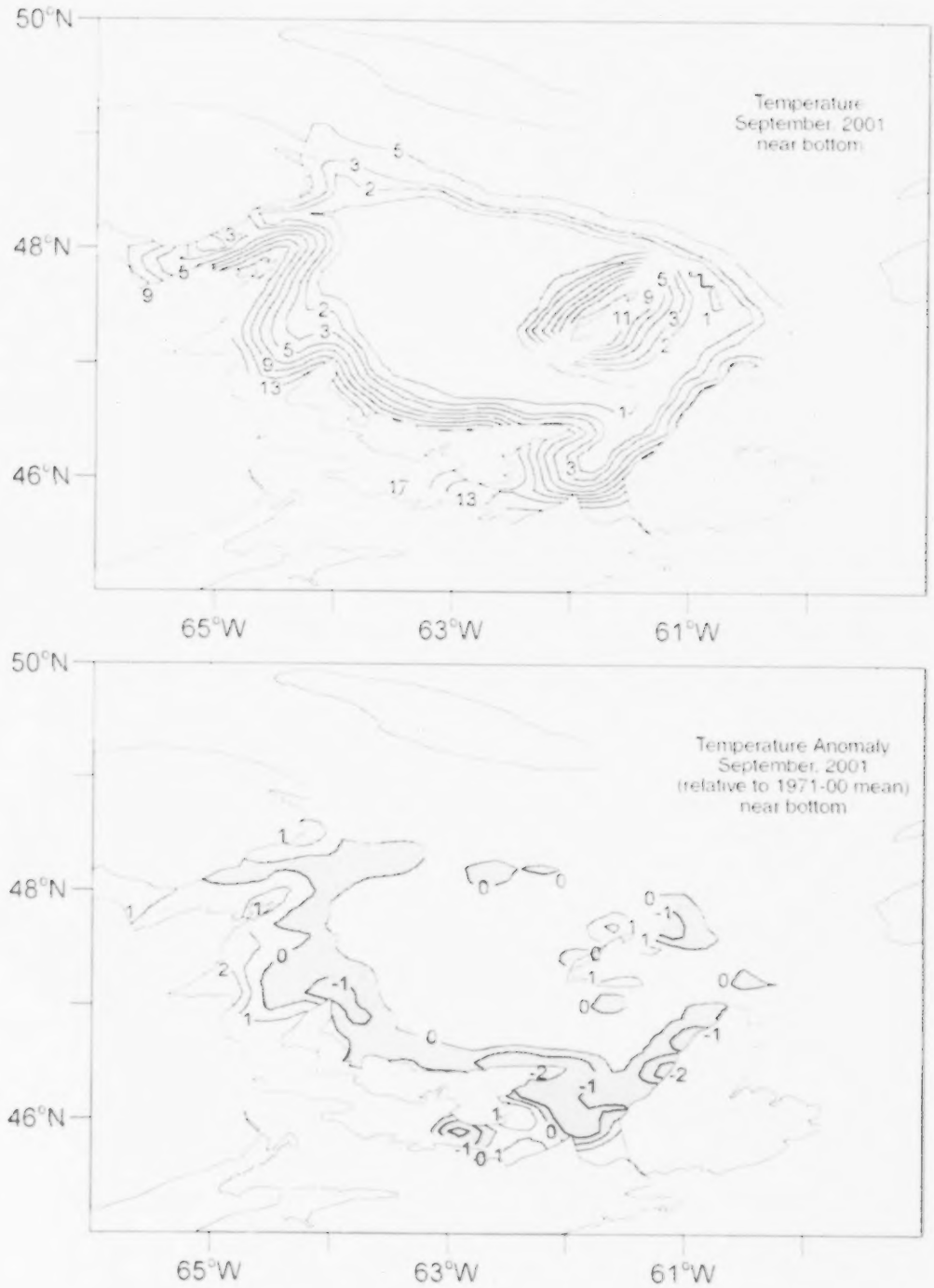

Fig. 12. Near-bottom temperatures (top panel) and their departure from the long-term (1971-2000) means (bottom panel) in the southern Gulf of St. Lawrence during the 2001 September groundfish survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

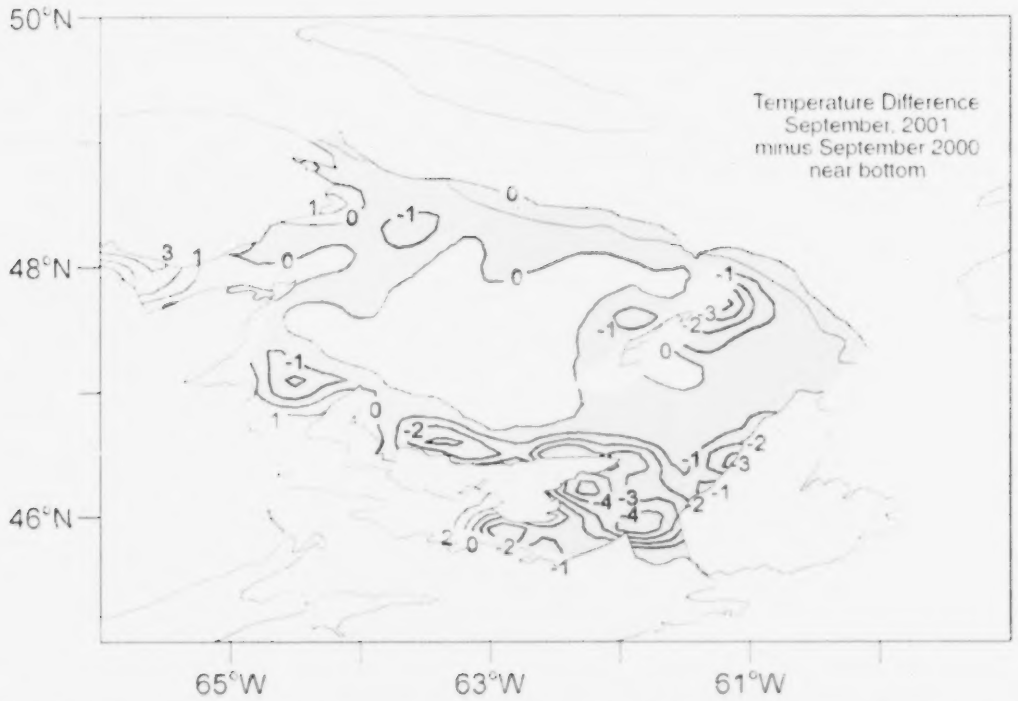

Fig. 13. The difference between the 2001 and 2000 temperature fields in the southern Gulf of St. Lawrence for the September groundfish surveys. Positive values indicate temperatures in 2001 had warmed and negative values that they had cooled. Regions where cooling occurred are shaded.

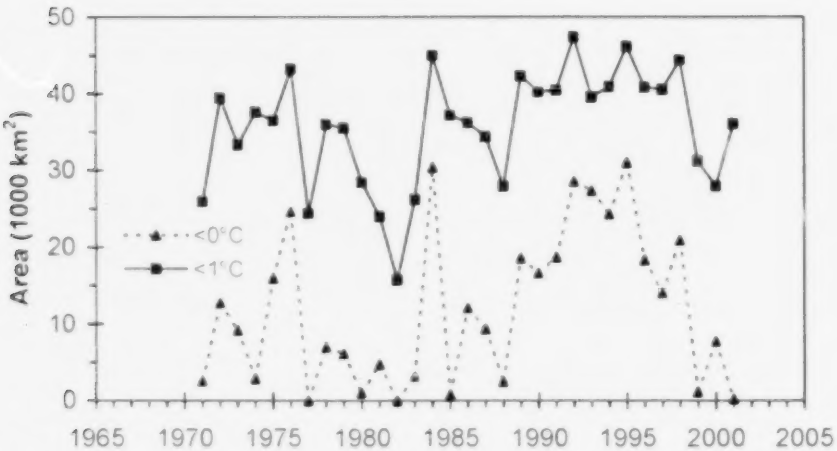

Fig. 14. Time series of the area of Magdalen Shallows covered by bottom temperatures < 0° and <1°C during the September groundfish surveys.

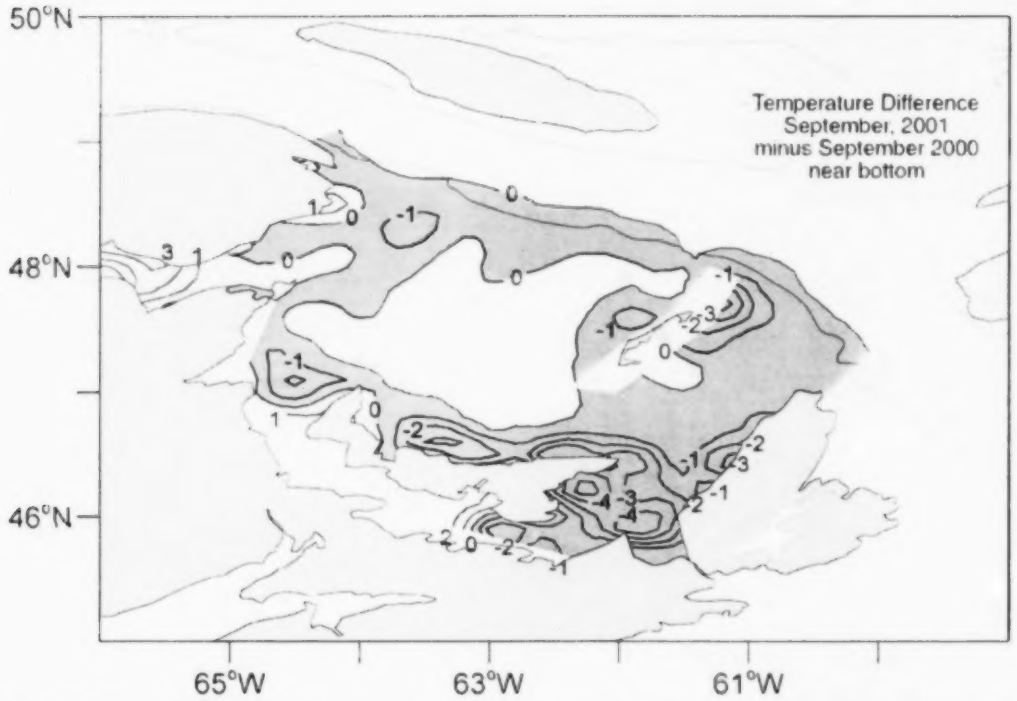

Fig. 13. The difference between the 2001 and 2000 temperature fields in the southern Gulf of St. Lawrence for the September groundfish surveys. Positive values indicate temperatures in 2001 had warmed and negative values that they had cooled. Regions where cooling occurred are shaded.

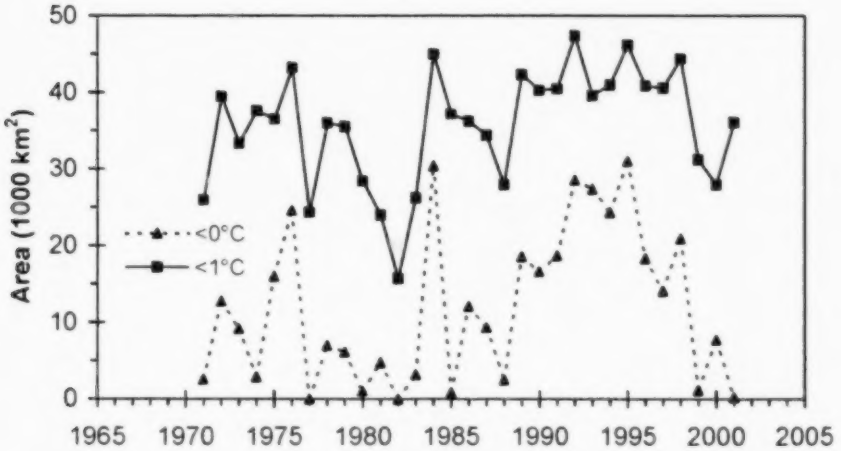

Fig. 14. Time series of the area of Magdalen Shallows covered by bottom temperatures < 0° and <1°C during the September groundfish surveys.

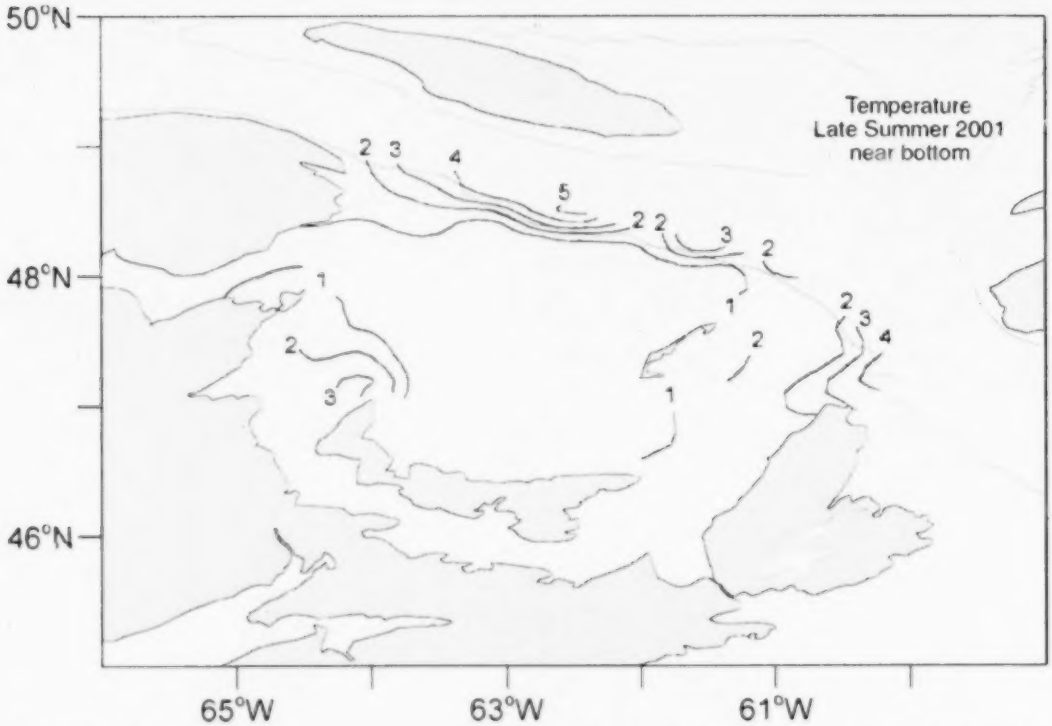

Fig. 15. Near-bottom temperatures in the southern Gulf of St. Lawrence during the 2001 August-October snow crab survey.

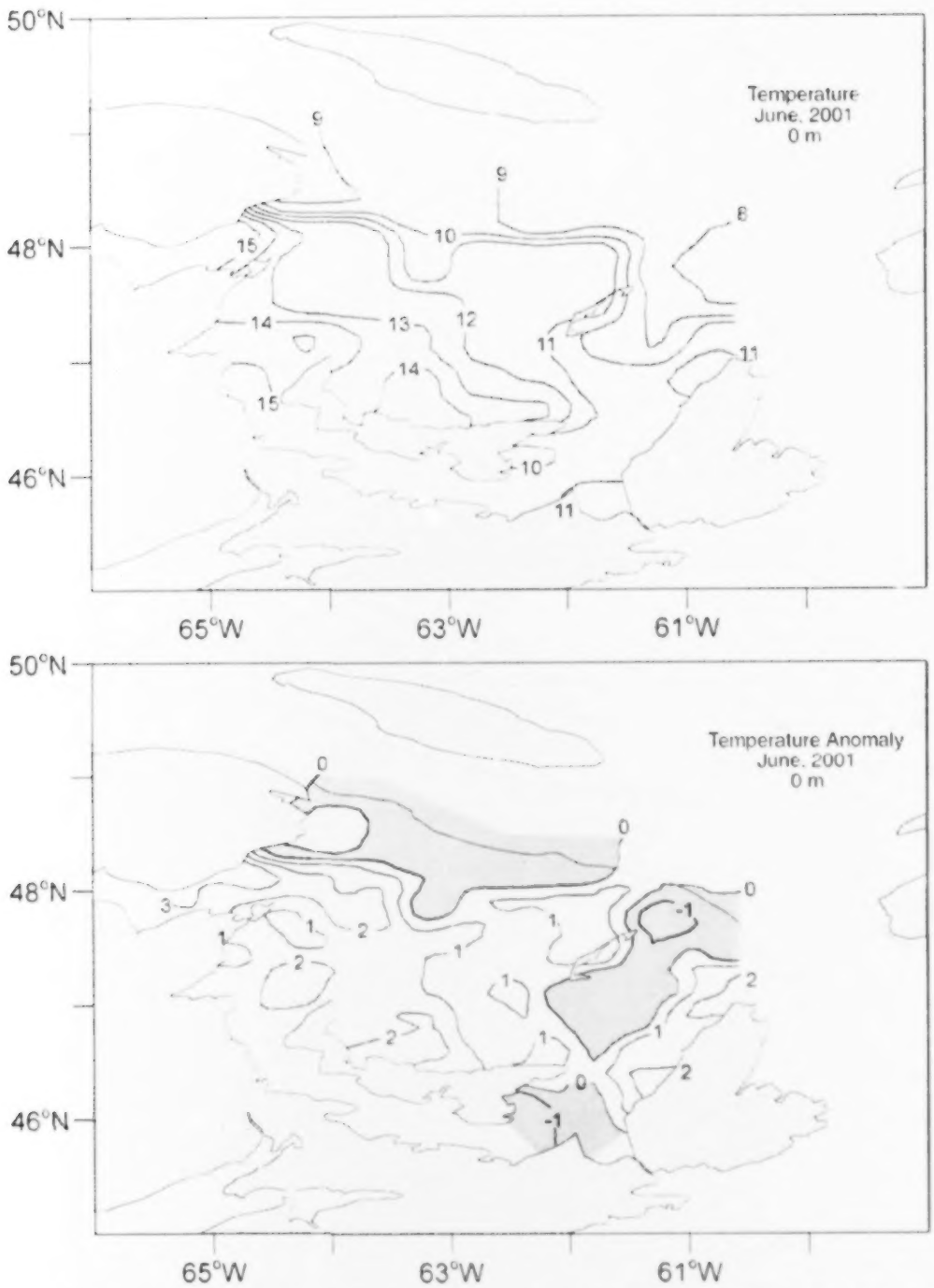

Fig. 16. Surface temperatures (top panel) and their departure from the long-term (1971-2000) means (bottom panel) in the southern Gulf of St. Lawrence during the 2001 June mackerel survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

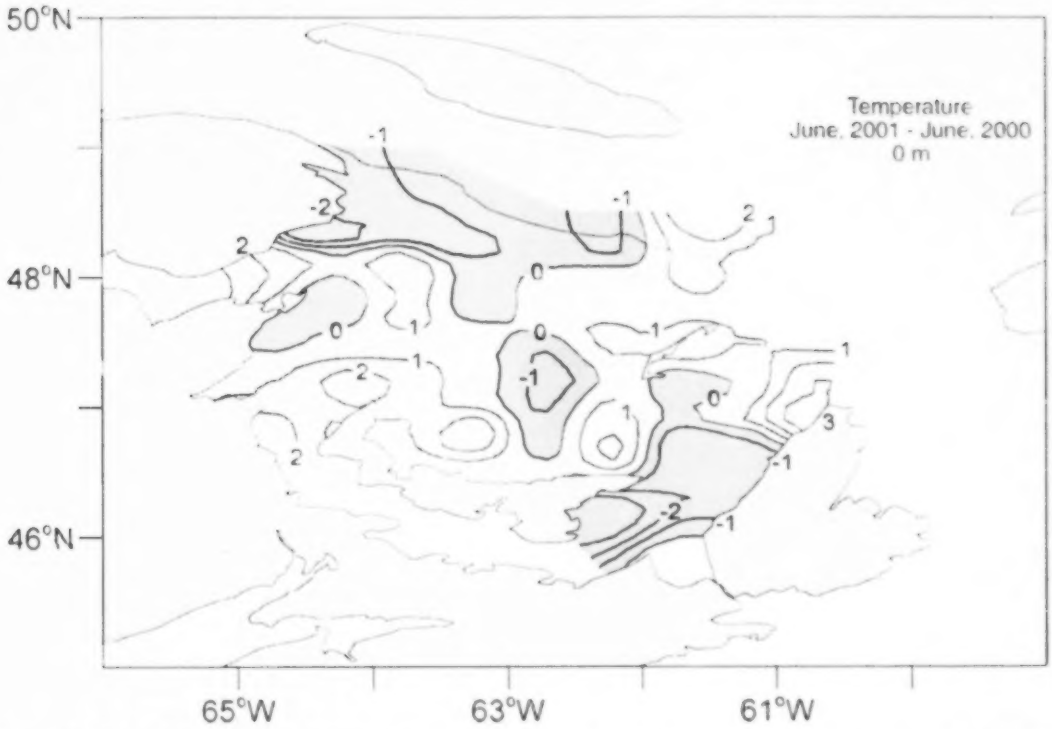

Fig. 17. The difference between the 2001 and 2000 surface temperatures in the southern Gulf of St. Lawrence during the June mackerel surveys. Positive values indicate temperatures in 2001 had warmed and negative values that they had cooled. Regions where cooling occurred are shaded.

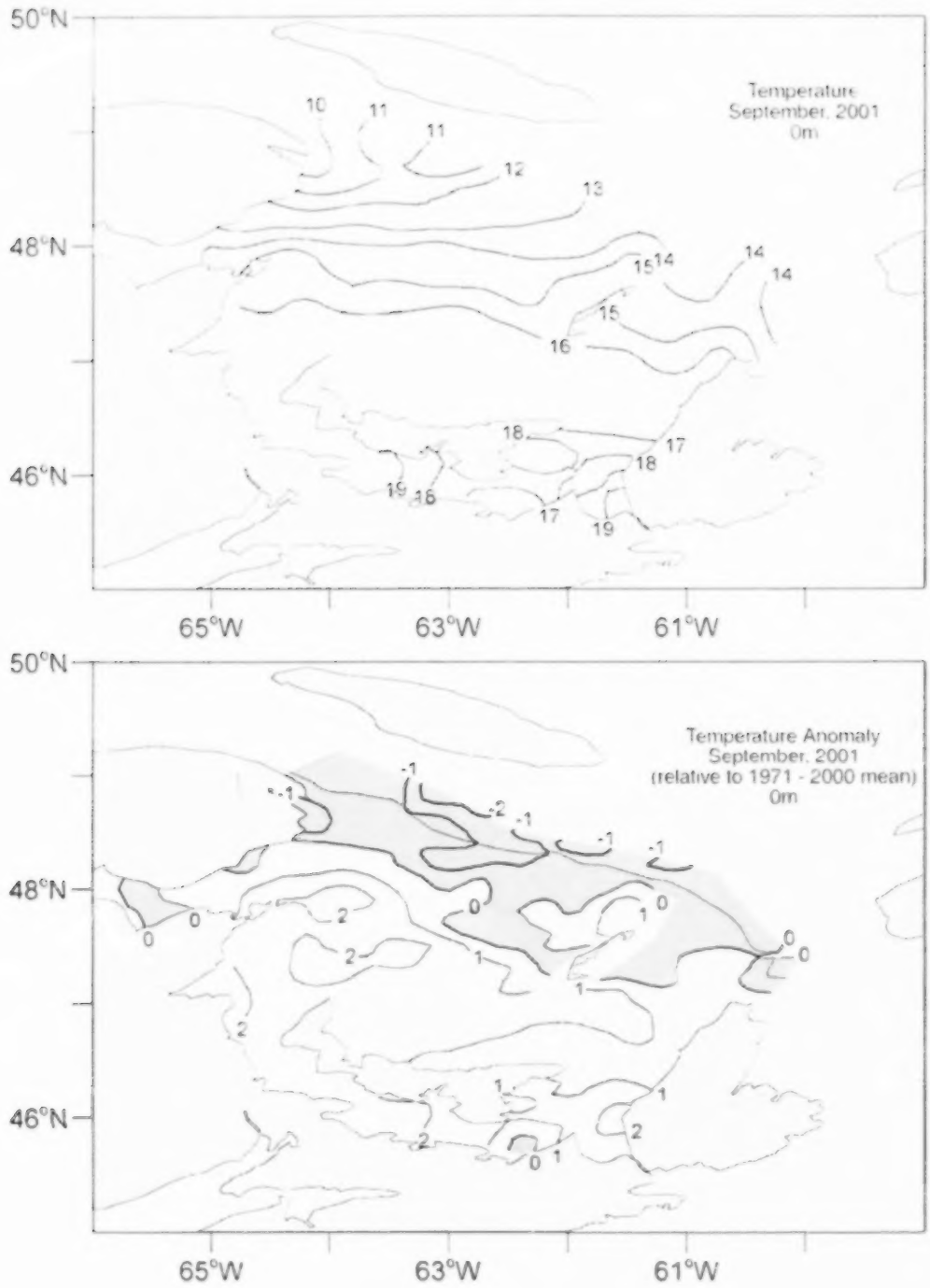

Fig. 18. Surface temperatures (top panel) and their departure from the long-term (1971-2000) means (bottom panel) in the southern Gulf of St. Lawrence during the 2001 September groundfish survey. Regions of colder-than-normal temperatures are shaded in the bottom panel.

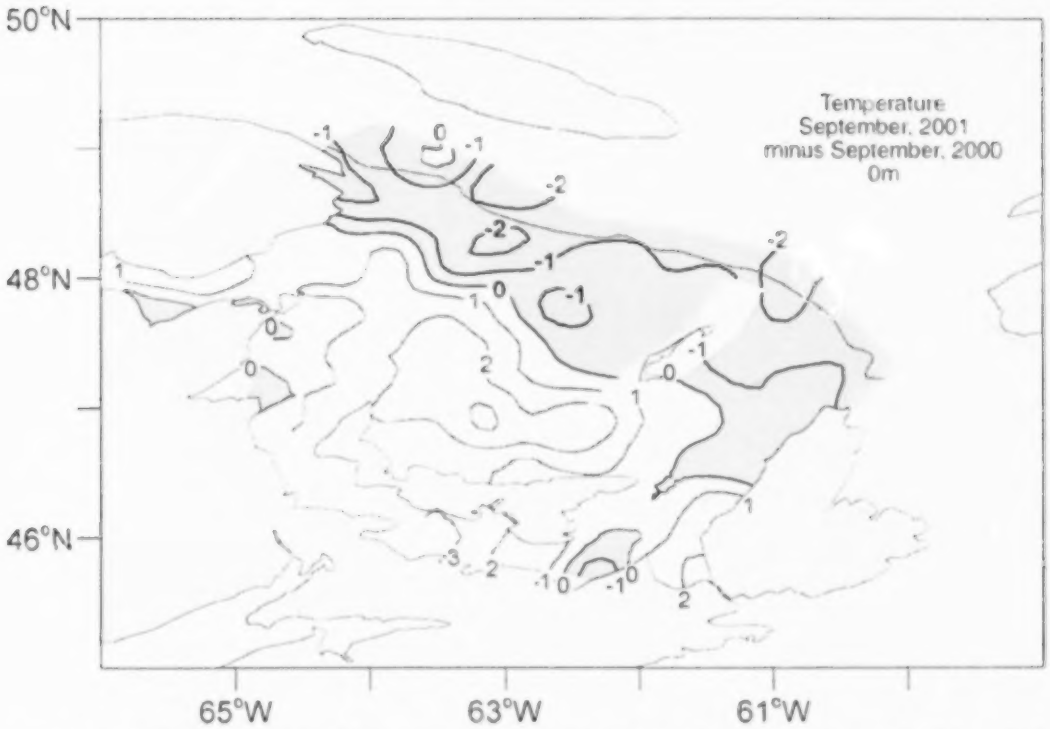

Fig. 19. The difference between the 2001 and 2000 surface temperatures in the southern Gulf of St. Lawrence during the September groundfish surveys. Positive values indicate temperatures in 2001 had warmed and negative values (shaded) where they had cooled.

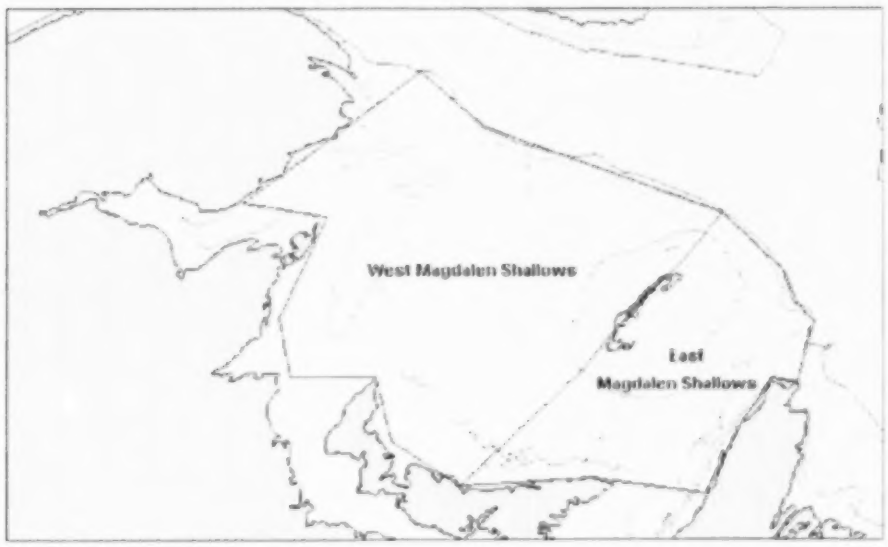

Fig. 20. The boundaries of the two regions of the Magdalen Shallows for which temperature and salinity analyses were carried out.

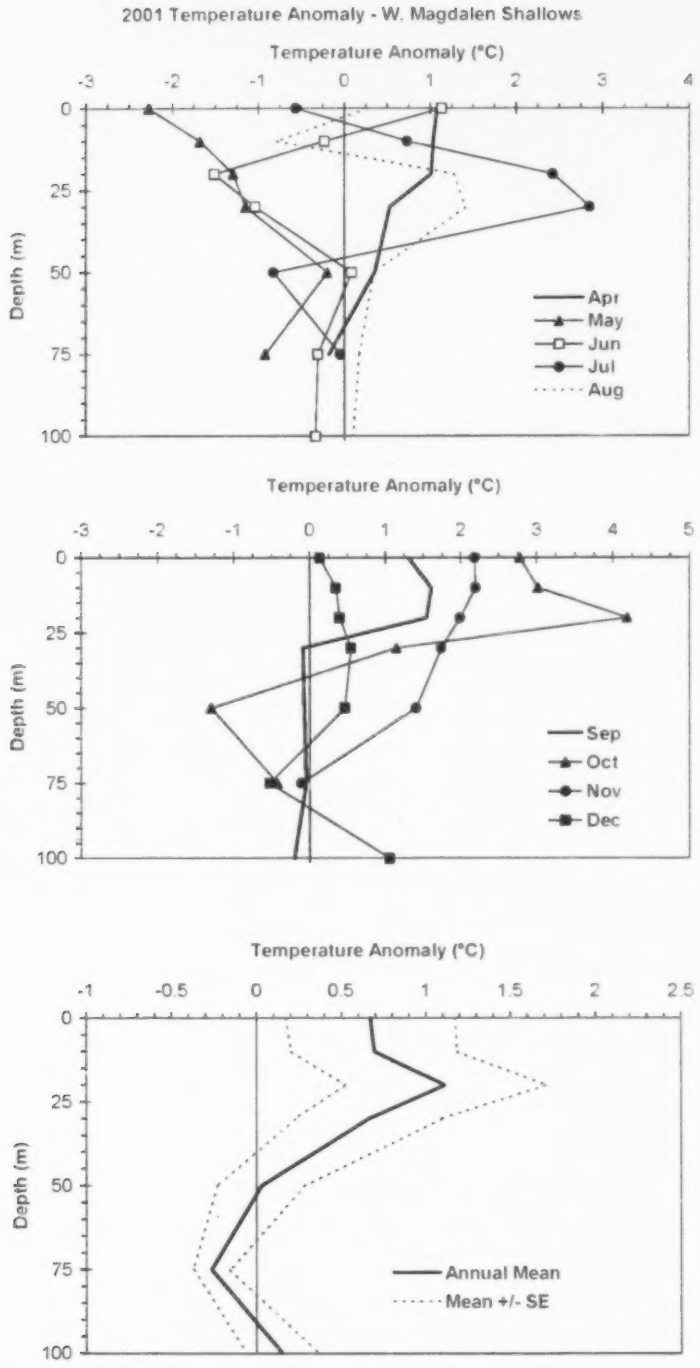

Fig. 21. The vertical profiles of the monthly (top panel) and annual (bottom panel) mean temperature anomalies during 2001 within the western Magdalen Shallows region (see Fig. 20 for boundaries). The dashed lines in the bottom panel display the mean ± the standard error of the mean.

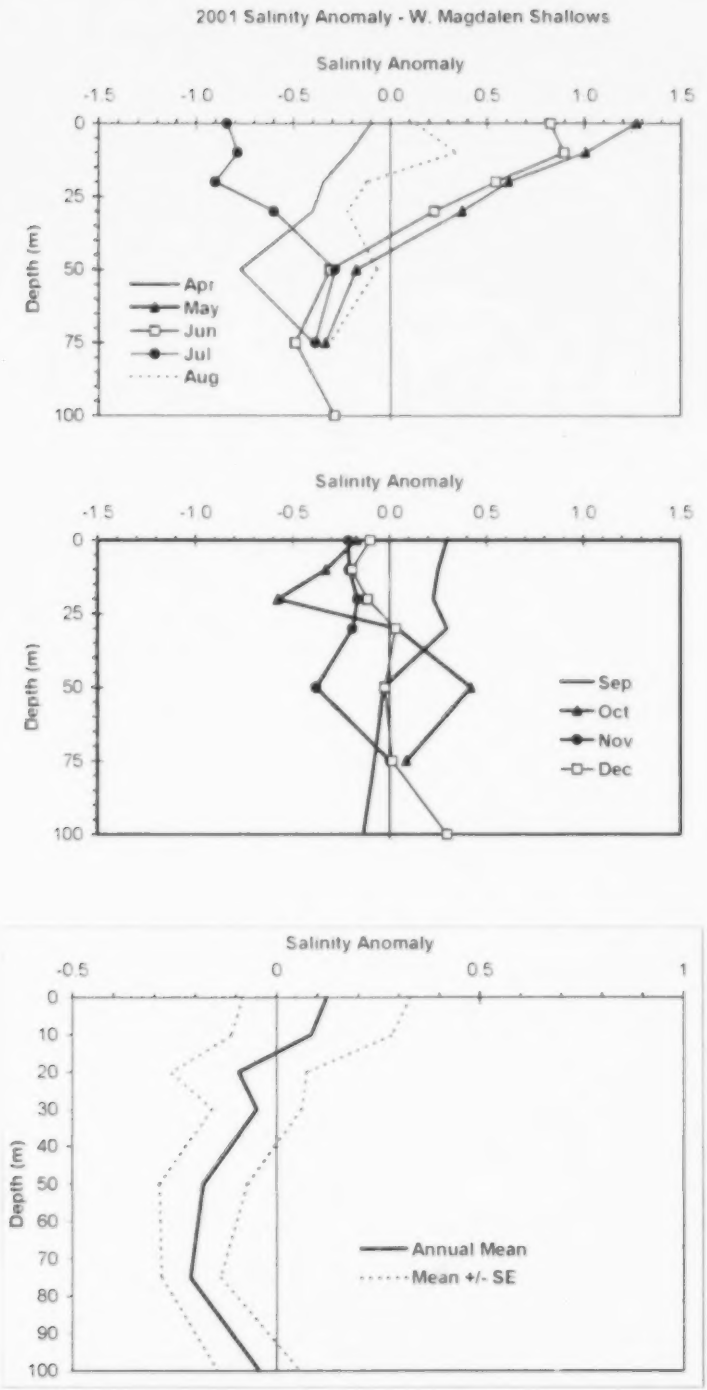

Fig. 22. The vertical profiles of the monthly (top panel) and annual (bottom panel) mean salinity anomalies during 2001 within the western Magdalen Shallows region (see Fig. 20 for boundaries). The dashed lines in the bottom panel display the mean ± the standard error of the mean.

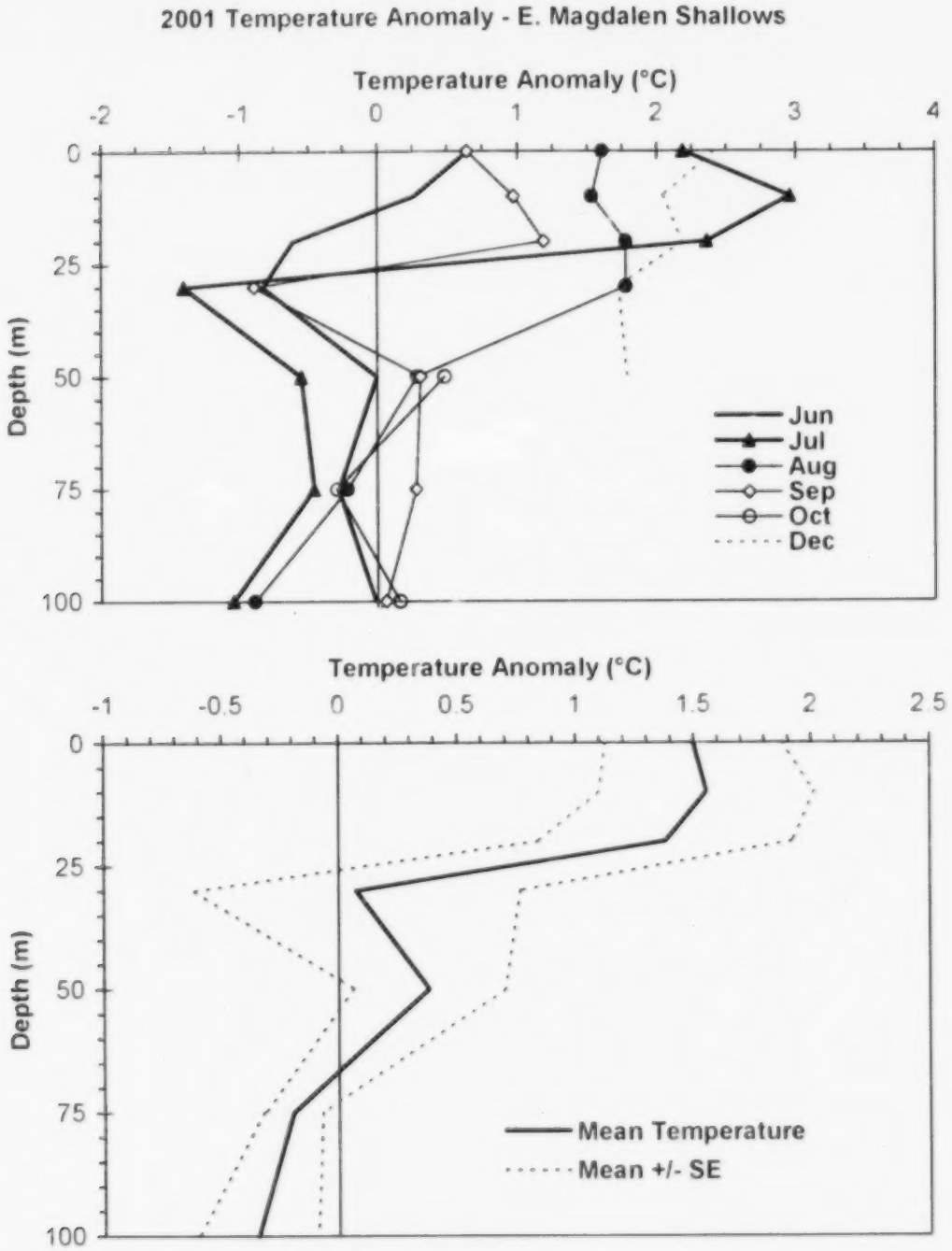

Fig. 23. The vertical profiles of the monthly (top panel) and annual (bottom panel) mean temperature anomalies during 2001 within the eastern Magdalen Shallows region (see Fig. 20 for boundaries). The dashed lines in the bottom panel display the mean ± the standard error of the mean.

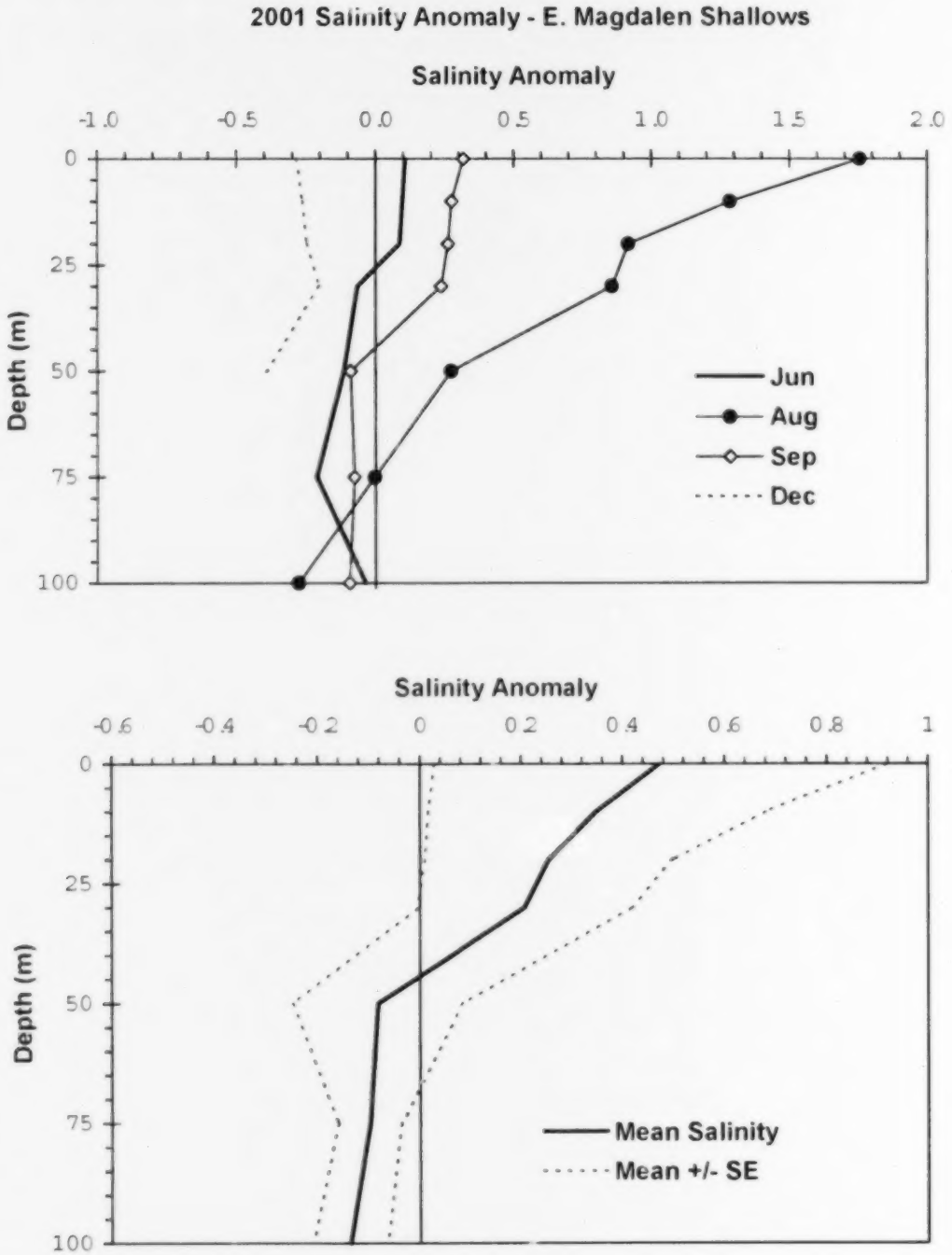

Fig. 24. The vertical profiles of the monthly (top panel) and annual (bottom panel) mean salinity anomalies during 2001 within the eastern Magdalen Shallows region (see Fig. 20 for boundaries). The dashed lines in the bottom panel display the mean ± the standard error of the mean.

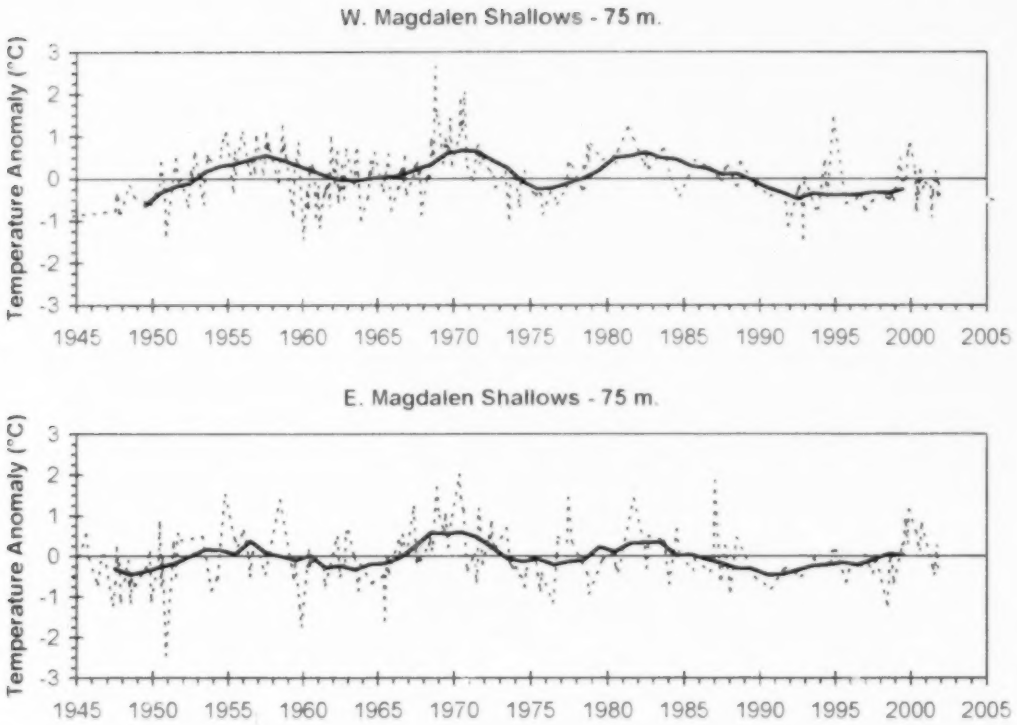

Fig. 25. The time series of the monthly (dashed line) and the 5-year running mean of the annual anomalies (solid line) of temperature at 75 m for the western (top panel) and eastern (bottom panel) Magdalen Shallows.

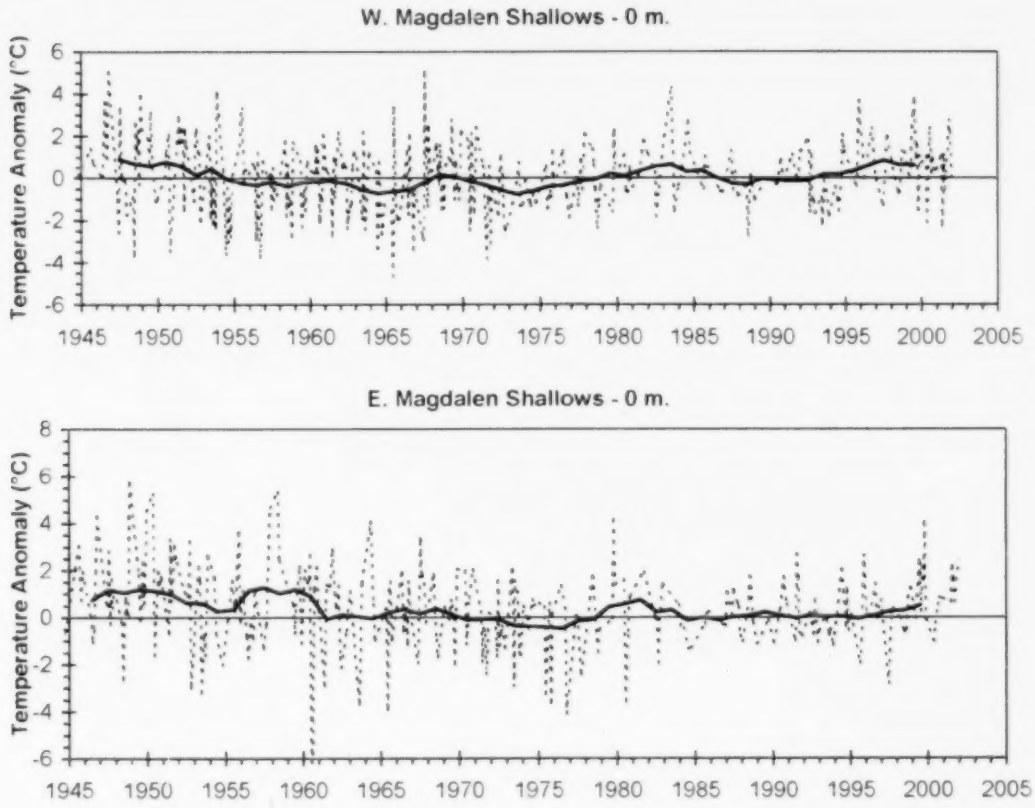

Fig. 26. The time series of the monthly (dashed line) and the 5-year running mean of the annual anomalies (solid line) of the surface temperature for the western (top panel) and eastern (bottom panel) Magdalen Shallows.

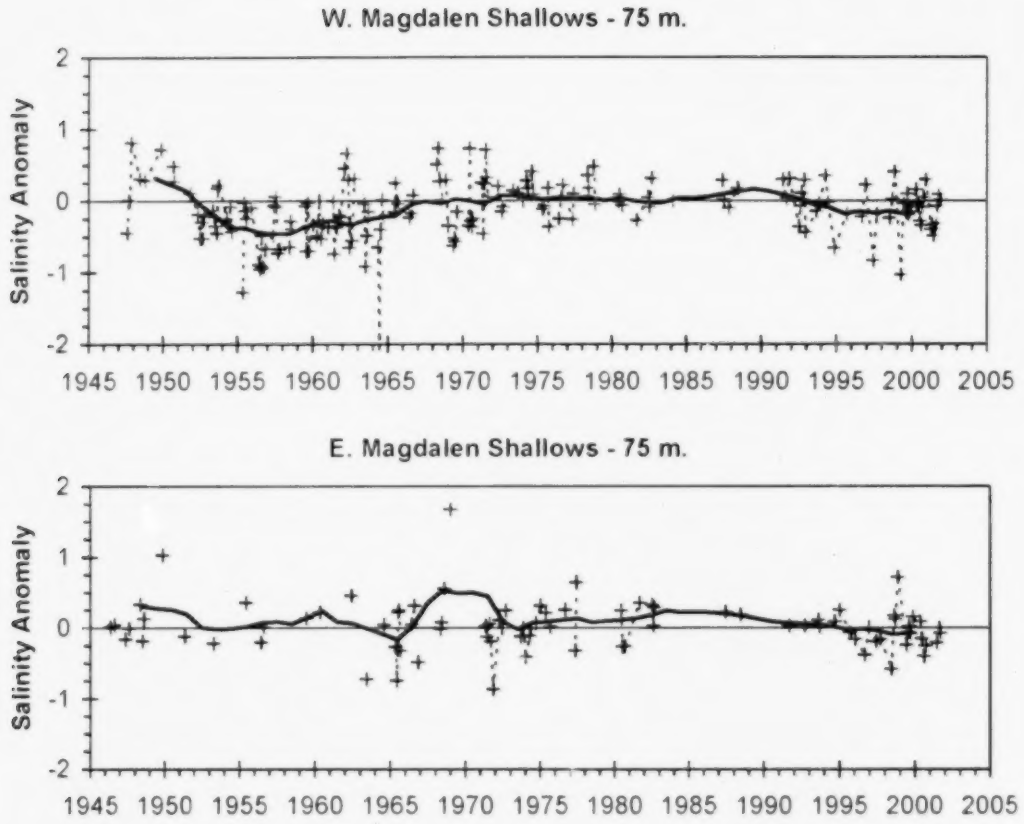

Fig. 27. The time series of the monthly (dashed line) and the 5-year running mean of the annual anomalies (solid line) of salinity at 75 m for the western (top panel) and eastern (bottom panel) Magdalen Shallows.

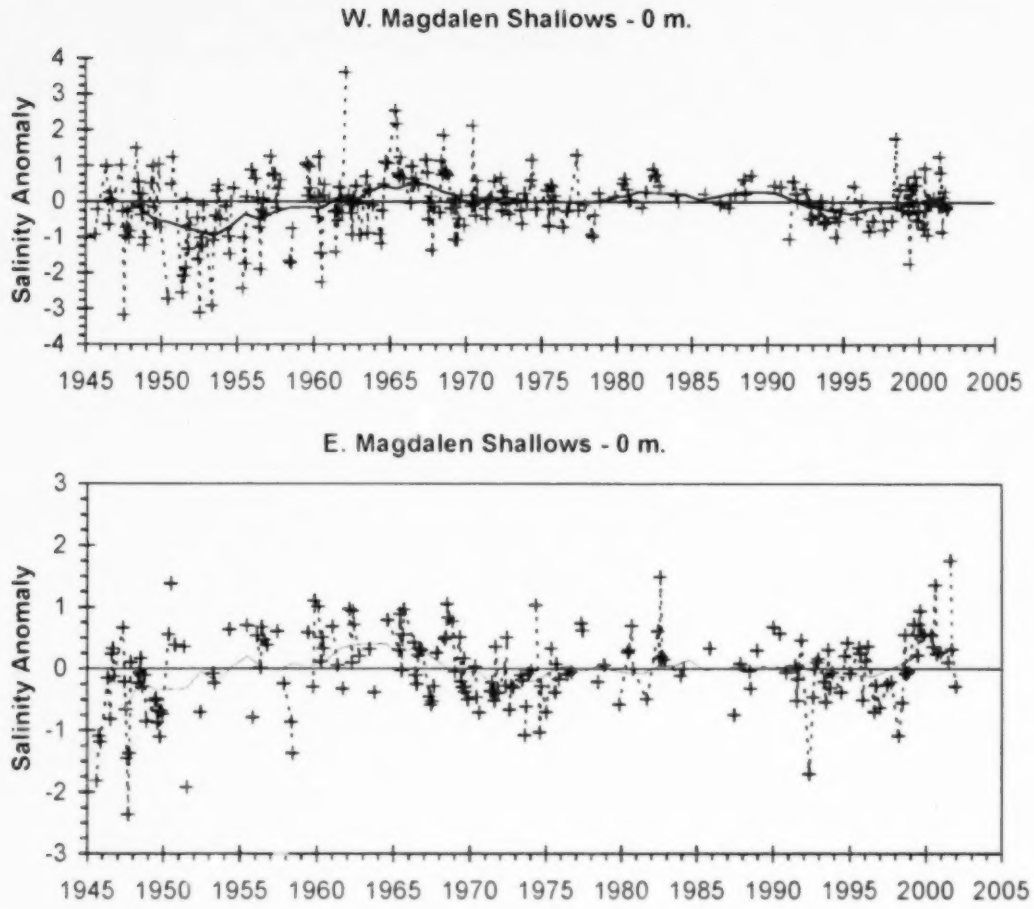

Fig. 28. The time series of the monthly (dashed line) and the 5-year running mean of the annual anomalies (solid line) of the surface salinity for the western (top panel) and eastern (bottom panel) Magdalen Shallows.

Fig. 29. Anomalies of the CIL core temperature (extrapolated to 15 July) for the Gulf of St. Lawrence relative to the 1971-2000 mean.